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Navigation Systems Research Program

A Procedure for Predicting the Deterioration of Steel Hydraulic Structures to Enhance their Maintenance, Management, and Rehabilitation

Guillermo A. Riveros, Elias Arredondo, Kevin Walker, DeAnna Dixon, Vince Fermo, Jeremy Davis, Chris Boler, and Lee Whitlow

June 2014

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Information Technology Laboratory
US Army Engineer Research and Development Center
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Final report

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Abstract

The deterioration of elements of steel hydraulic structures on the Nation's lock system is caused by combined effects of several complex phenomena: loss of protective system, corrosion, cracking and fatigue, impact, and overloads. This report presents a method for predicting future deterioration based on current conditions of the navigation structure. The report includes a procedure for developing deterioration curves when condition state data is available. Finally, the report serves as the user's manual for the Navigation Structure Inventory Management System (NAVSIMS) that is a web-base program developed to store the element base inspection reports and it generates the deterioration curves to predict the future condition of the navigation steel structures.

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Preface

This research was conducted under the Navigation Systems Research Program, Work Unit 291GD8 for which Dr. Guillermo A. Riveros was the principal investigator, and “Navigation Structures Inventory Management System (NAVSIMS).” The Program Manager was Charles Eddie Wiggins, Associate Technical Director, Coastal and Hydraulics Laboratory (CHL), US Army Engineer Research and Development Center (ERDC), Vicksburg, MS.

This report was prepared by Dr. Guillermo A. Riveros, Elias Arredondo, Kevin Walker, Deanna Dixon, Vince Fermo, Jeremy Davis, Chris Boler, and Lee Whitlow, Information Technology Laboratory (ITL), ERDC. The report was prepared under the general supervision of Elias Arredondo, Branch Chief, Computational Analysis Branch, ITL; Dr. Robert M. Wallace, Chief, Computational Science and Engineering Division, ITL; David R. Richards, Technical Director, Computational Science and Engineering, ITL; Patti S. Duett, Deputy Director, ITL; and Dr. Reed L. Mosher, Director, ITL.

At the time of the publication of this report, COL Jeffrey R. Eckstein was Commander of ERDC and Dr. Jeffery P. Holland was the Executive Director of ERDC.

1 Description and Background Information

Introduction

The inland waterway system has been developed gradually throughout the Nation's history. Locks and dams were constructed to raise water levels and provide a more reliable channel on the Nation's main rivers and tributaries. Today a system of 192 lock sites, with 238 lock chambers, provides a minimum 9-foot navigation channel on nearly 12,000 miles of inland and intracoastal waterways (HQUSACE 2000; Grier 2009). This system is operated and maintained by the US Army Corps of Engineers (USACE) as part of its civil works program. This waterway network is mainly used by commercial towboats, which push barges lashed together as tows, with each barge capable of holding 1400-1800 tons of cargo. A single tow of 15 barges carries the freight cargo equivalent of 870 tractor trailer trucks, making this a low-cost and fuel-efficient freight mode that is especially suited to bulk cargo that is not time-sensitive (Grier 2009) as seen in Figure 1.

Figure 1. Map of the inland and intracoastal waterway system.

The deterioration of elements of steel hydraulic structures on the Nation's lock system is caused by combined effects of several complex phenomena: loss of protective system, corrosion, cracking and fatigue, impact, and overloads.

In the absence of a mechanistic-based deterioration model that requires quantitative contribution of these complex phenomena based on environmental effects and maintenance constraints, steel hydraulic structures' (SHS) inspection data can be used to determine the need for rehabilitation or replacement and prioritize the order of work and funding. This can be accomplished by the use of deterioration models (Bulusu and Sinha 1997; Madanat et al. 1995; Madanat et al. 1997; Morcous et al. 2002).

Information on current and future conditions of navigation or flood-control SHS is essential for the maintenance and rehabilitation of our navigation infrastructure. Current conditions of our navigation infrastructure are measured by periodic and detailed inspections following recommendations from Engineer Regulation (ER) 1110-2-100, Periodic Inspection and Continuing Evaluation of Completed Civil Works Structures (HQUSACE 1998); ER 1110-2-8157, Responsibility for Hydraulic Steel Structures (HQUSACE 2009); and EM 1110-2-6054, Inspection, Evaluation, and Repair of Hydraulic Steel Structures (HQUSACE 2001).

The accuracy of these conditions depends on the type of inspection performed. On occasion, detailed inspections are conducted when a problem is perceived by the operators. In some cases, the deterioration of the SHS has been found to be critical and emergency repairs and contingencies have been conducted. This reactive approach will usually incur more cost. These emergency repairs could be avoided if a proactive approach (e.g., a deterioration model) is used to predict the future condition of the structure. The prediction will indicate when the structure will fall below a satisfactory performance level and when its condition may become severe if the structure is not maintained properly. Accurate predictions of the condition of the structure in the future are essential to maintain the inventory on a safe and reliable level of performance.

Methods for predicting infrastructure deterioration can be categorized into deterministic- and probabilistic-based models. Deterministic-based models are those in which no randomness is involved in the development of future deterioration states of the system. These models calculate the condition of the system as a precise value based on mathematical formulations of the actual deterioration (Ortiz-Garcia et al. 2006). Probabilistic-based models consider the deterioration states of the system as random variables and they are modeled by underlying probability distributions (Agrawal et al. 2008).

Research Significance

Engineer Regulation 1110-2-8157 (HQUSACE 2009) requires USACE districts to conduct inspections, record inspection information, and to archive the information for future reference. The information is used for evaluation of condition determination of maintenance, repairs, and replacement needs.

The ultimate goal of this research is to provide a tool that USACE Head Quarters, Divisions, and Districts can use for collecting and assessing inspection data in a consistent manner that leads to uniform evaluations across districts. The information will be stored in a centralized location and can be used to generate a variety of reports. Aggregate information can then be used to predict future deterioration and to set priorities for maintenance, repairs, and replacement.

Purpose

This report proposes a Health Systems Strengthening (HSS) Inspection, Reporting, and Evaluation System that provides a systematic approach to identifying, documenting, and tracking deficiencies in HSS; a means to predict useful performance, and a tool to predict the future condition for prioritizing maintenance and replacement funding. The information gathered is directly applicable to database application for storing information, tracking changes, measuring performance, making uniform comparisons across different locations, aiding in the decision-making process, and making risk and reliability evaluations possible. The collection of data must be as objective and repeatable as possible by using standard information-gathering procedures and describing conditions using standard technical language and terminology. These standards promote consistency in data gathered, which results in consistent and objective evaluations and comparisons across District boundaries. The components that make up the system and their interaction will be described later in this report.

Overview

This Technical Report is organized as follows. Chapter two briefly describes the steel hydraulic structures most commonly used in navigation and flood control projects and presents examples of the different types of deteriorations most commonly encountered on SHS. It also describes the deterioration states developed for SHS. Chapter three presents the mathematical description of the Markov chain prediction model, as well as a proposed method to calculate transition probabilities. This chapter also presents an example of how to develop the deterioration curves for the cases when a limited amount of data is available. Chapter four presents the user's manual for the Navigation Structures Informatics Management System (NAVSIMS). Chapter five summarizes and concludes the findings of the work. An example of NAVSIMS is presented in Appendix A.

2 Deterioration of Steel Hydraulic Structures

Introduction

US Army Corps of Engineers currently operates 192 lock sites, with 238 lock chambers that include various steel hydraulic structures (SHS), many of which are near or have reached their design life. Structural inspections and evaluations are required to assure that adequate strength and serviceability are maintained at all sections as long as the structure is in service (HQUSACE 2001).

Lock gates are moveable gates that provide a damming surface across a lock chamber. Most existing lock gates are miter gates (Figure 2), vertical-lift gates (Figure 3), with a small percentage being sector gates (Figure 4), and submergible tainter gates (Figure 5). Spillway gates are installed on the top of dam spillways to provide a moveable damming surface allowing the spillway crest to be located below a given operating water level. Such gates are used at locks and dams (navigation projects) and at reservoirs (flood control or hydropower projects). Spillway gates are generally tainter gates (Figure 6), the most common, or lift gates, but some projects use roller gates.

Deterioration Examples of Steel Hydraulic Structures

The following brief examples illustrate the potential results of casual inspection combined with inattention to deterioration of different components of SHS.

Figures 7 and 8 show some particularly bad corrosion occurring in miter gate compartments that are normally above the water line. In Figure 8, the coating has not been kept in good condition, and thus allowing general corrosion to occur.

Figure 8 offers an illustration of the adverse affects of corrosion inside a lock miter gate compartment. This figure (Figure 8) shows that this particular miter gate has not had an impressed current cathodic protection system for many years. If the protective system is not preserved and repairs are not performed periodically, it will lead to a significant amount of section loss, due to corrosion, that may require an emergency closure for repairs and maintenance.

Figure 2. An example of a horizontally framed miter gate.

Figure 3. John Day Lock, Columbia River, a vertical lift gate.

Figure 4. Leland Bowman Lock, Gulf Intracoastal Waterway (GIWW), a Sector gate.

Figure 5. View of the downstream side of the body of the tainter gate and one arm and trunnion of the gate which is used for the lock service gate at the upper end of St. Anthony Falls Lock on the Mississippi River.

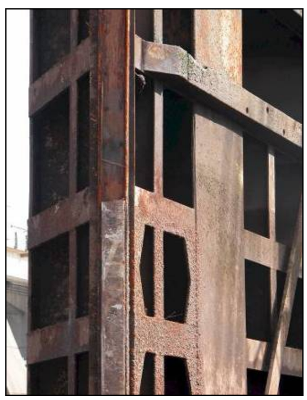
Figure 6. View of the downstream side of the Carlyle Lake tainter gates.

Figure 7. Corrosion on a miter gate.

Figure 8. Corrosion inside a lock miter gate compartment.

Quoin block deterioration analysis conducted by Riveros et al. (2009) demonstrated that deterioration in the quoin block (Figure 9) could drastically affect the state of stresses on the elements transferring loads to the pintle and the pintle connection.

Figure 9. Quoin block failure.



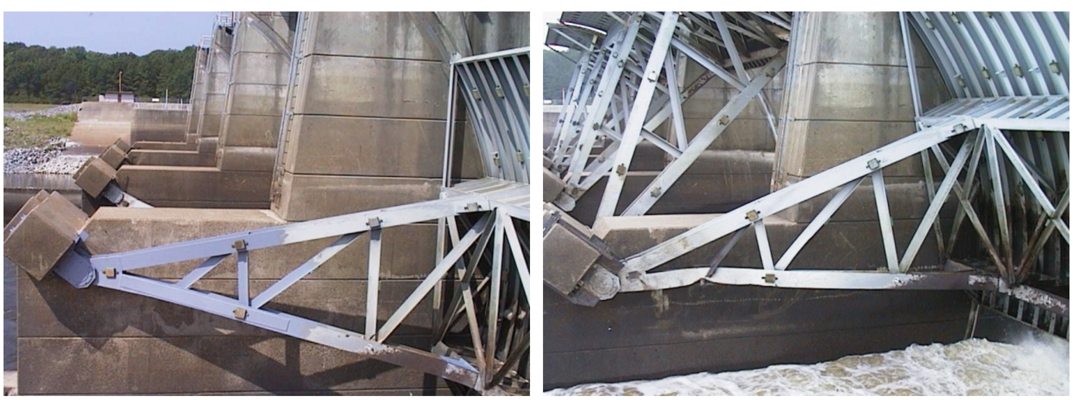
If the deterioration is severe, the stresses can reach undesirable levels. The location of the stress concentrations depend on the quoin deterioration area: if the deterioration occurs in the pintle area (bottom section of quoin block), the maximum stresses will be generated in the pintle zone; and if the deterioration is in the upper region of the quoin block, the maximum stress will be generated in the elements near the quoin block effective area end. This deterioration will cause some elements such as the thrust diaphragm, thrust diaphragm stiffeners, end diagrams, and the pintle connection to be overloaded due to the redistribution of the forces not being transmitted to the wall when the gate is in the miter position. In some cases, some of these elements have shown buckling failures and out of plane distortion when severe deterioration of the quoin block is present.

Barge impact is one of the main concerns regarding navigation infrastructures (Figure 10), since they occur without prior warning.

Figure 10. A Belleville Locks & Dam Barge Impact.

Figure 11 shows a tainter gate with strut arm damage due to a barge impact and after the repairs done to the strut arm.

Figure 11. Tainter gate with strut arm damage due a barge impact and after the repairs were made.



Failure of the project operating systems can render lock and flow control gates inoperable, causing delays to river traffic or possible overtopping of the project. Structural failure of a lock gate could severely impede or stop river traffic. Catastrophic failure of a spillway gate, dewatering bulkhead, or a lock gate could cause uncontrolled release and/or loss of pool, resulting in loss of life (HQUSACE 2009).

Additionally, it would be necessary to close that section of the river to navigation traffic, disrupting the movement of products, thus, impacting the towing industry. If the impact generates a long closure of the lock, the industry may have to find alternative routes or sources of transportation, decreasing production, lost sales, and also causing loss in revenue, in addition to the extra cost to the government on labor hours for the repairs.

In many cases, the primary form of distress has been fatigue damage and fracture. The most common causes of fatigue cracking have been a lack of proper detailing during design, poor weld quality during fabrication, and poor detailing and execution of repairs. Recent inspections by districts have indicated that a significant number of stop logs and bulkheads had deficient welds which required repairs. Additionally, the deterioration of the design boundary conditions and unexpected loading conditions (Figure 12) has caused stresses to be redistributed to other elements, which has caused cracking, especially near the lower pintle socket. Many of these deficiencies were the result of ineffective quality control during the original welding fabrication of the structures (Figure 13 and 14).

Figure 12. Unexpected loading conditions.

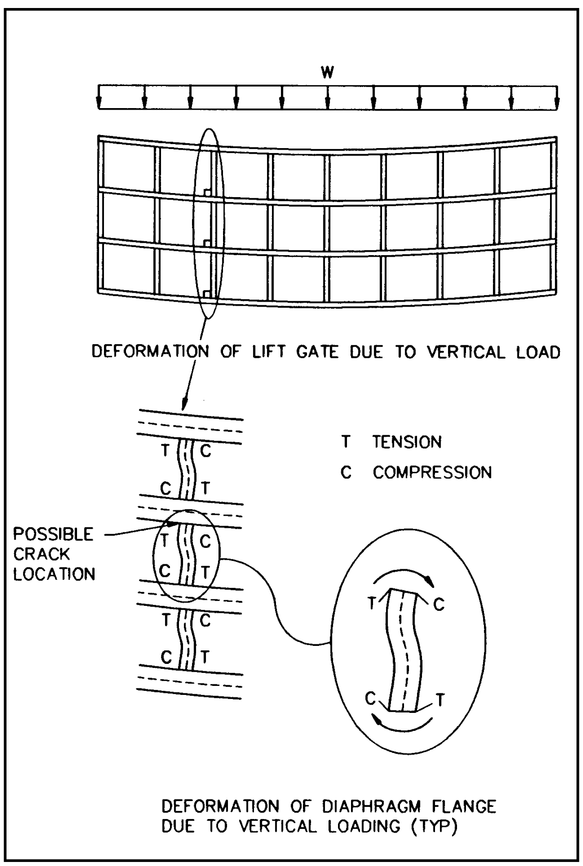


Figure 13. Fatigue crack at Diaphragm Flanges of a miter gate.

Figure 14. Fatigue crack in Girder Flanges of a miter gate.

Condition states for steel hydraulic structures

Infrastructure condition is often represented by discrete condition states (Madanat et al. 1995). Condition states have been used to define the condition of individual components of bridges and sewer pipes (Agrawal et al. 2008; Federal Highway Administration (FHWA) 1995; American Association of State Highway and Transportation Officials (AASHTO) 2002; Thomson and Shepard 2000). New York State Department of Transportation uses a rating system (condition states) from 1-7, where 7 represents near-perfect conditions and 1 represents a state of failure (Agrawal et al. 2008). AASHTO (2002) recommends a rating system from 1-5, where 1 is near-perfect condition and 5 represent a state of failure. Sauser and Riveros (2009) developed a condition rating system similar to that in AASHTO (2002) for SHS that uses an ordinal integer-value scale from 1 to 5. This system indicates relative health of the infrastructure elements for the four most common deteriorations encountered in SHS: protective system, corrosion, fatigue and fracture, and impact or overloads. The overall condition rating of the entire structure is computed by a weighted average of the individual element condition ratings and is a function of selected weights. The selection of appropriate weights is driven by sound engineering reasons, such as the importance of fracture-critical members, primary members, pintle, etc.

Corrosion and section loss can be described in the following stages:

- The member is protected by a protective coating, other means, or has not been subjected to corrosive action. The member is in like-new or as-built condition and has no deterioration.
- The member has lost some of its protection or has been subjected to corrosive action and is beginning to deteriorate (corrode) but has no measurable section loss. Deterioration does not impact function. This state is bounded minimally by the onset of corrosion and maximally by section loss that is not measurable, e.g., pitting not measurable by simple hand tools.
- The member continues to deteriorate and measurable section loss is present but not to the extent that it affects its function. The upper bound of this state is, for example, pitting to a depth less than 1.5875 mm (0.0625 in.) or total loss of section thickness less than 3.175 mm (0.125 in.).
- The member continues to deteriorate, and section loss increases to the point where function may be affected. An evaluation may be necessary to determine if the structure can continue to function as intended, if repairs are needed, or if its use should be restricted. The upper bound is a function of member strength, member load, and member use, but it could be capped at 10 percent of total section loss for ease of and consistency in reporting.
- The member continues to deteriorate and section loss increases to the point where the member no longer serves its intended function and safety is affected. An evaluation may be necessary to determine if the structure can continue to function safely. The five general condition states are listed in Table 1.

Table 1. Five Condition States

No.	Condition	Description
1	Protected	Member is sound, functioning properly, and absent of deficiency.
2	Exposed	The member shows beginning signs of deficiency but is still sound and functions as intended. There is no impact to performance or reliability.
3	Attacked	Deficiency has advanced and the member still functions as intended but continued, unabated deterioration will lead to the next condition state.
4	Damaged	Deficiency has advanced to the point that function may be impaired.
5	Failed	Deficiency has advanced to the point that the member no longer serves its intended function and safety is impacted.

3 Predicting Deterioration of Navigation Steel Hydraulic Structures with Markov Chain and Latin Hypercube Simulation

The literature revealed that Markov models are extensively used for infrastructure deterioration (Madanat et al. 1995; Micevski et al. 2002; DeStefano and Grivas 1998) with bridges being a frequent candidate (Agrawal et al. 2008) followed by pavements (Ortiz-Garcia et al. 2006), and sewer pipes (Micevski et al. 2002; Baik et al. 2006). The Markov chain prediction model is a stochastic process that is discrete in time, has a finite state space, and establishes that future state of the process depends only on its present state.

Markov Chain Prediction Model Applied to Steel Hydraulic Structures

Applying the Markov process to predict the deterioration of navigation structures involves the following observations and assumptions:

- The deterioration process of a structure is continuous in time; however, to render it discrete in time, the condition is usually analyzed at specific periods. For SHS these periods correspond to periodic and detailed inspections.
- The condition of a structure can have an infinite number of states. But in reality, the condition of a SHS is defined by a finite set of numbers (Sauser and Riveros 2009) such as 1, 2, 3, 4, and 5, where 1 represents the structure is in its best condition possible and 5 represents imminent failure of the structure.
- The future condition of a SHS is assumed to depend only on its present condition and not on its past conditions.

Definition of Markov Chain:

$$P\left(X_{t+1}=i_{t+1} \mid X_t=i_t,\ X_{t-1}=i_{t-1,\dots,}\ X_1=i_1,\ X_0=i_0\right)= P\left(X_{t+1}=i_{t+1} \mid X_t=i_t\right) \quad (1)$$

where P is a function of X representing the probability to change from state i to state j at time t+1, for all deterioration states $i_0,i_1,\ldots,i_{t-1},i_t,i_{t+1}$ and all $t \geq 0$.

Markov chain is considered to be homogeneous if the probability $p_{i,j}$ going from state i at time t to state j at time (t + 1) is independent of t.

For all states, i and j, and all t,

$$P\left(X_{t+1} = j \mid X_t = i\right) = p_{i,j} \tag{2}$$

The transition probabilities are expressed as an $m \times m$ matrix called the transition probability matrix. The transition probability matrix, P, is defined as the following:

$$P = \begin{bmatrix} p_{1,1} & p_{1,2} & \cdots & p_{1,m} \\ p_{2,1} & p_{2,2} & \cdots & p_{2,m} \\ \vdots & \vdots & \vdots & \vdots \\ p_{m,1} & p_{m,2} & \cdots & p_{m,m} \end{bmatrix} \tag{3}$$

The probability that the system goes from state i to state j after t periods can be obtained by multiplying the probability matrix, P, by itself t times.

$$P_t = P^t \tag{4}$$

If Q_0 is the initial state vector,

$$Q_0 = \left[q_1, q_2, \ldots, q_m\right]$$

and q_i represents the probability of being in state i at time 0;

then the state vector, Q_t, representing the state at time t can be expressed as the following:

$$Q_t = Q_0 \bullet P^t \tag{5}$$

If the system is in the first state at time 0, Q_0 can be expressed as

$$Q_0 = \left[1,0,0,0,0\right]$$

Indicating that the probability of the system being in the first state is equal to 1 (or 100%) and the probability of any other state is 0.

Similarly, if the system is in the second state, Q_0, can be expressed as

$$Q_0 = [0,1,0,0,0]$$

Indicating that the probability of the system being in the second state is equal to 1 (or 100%) and the probability of any other state is 0.

Defining a vector of condition ratings as

$$R = \begin{bmatrix} 1 & 2 & 3 & 4 & 5 \end{bmatrix} \tag{6}$$

The condition rating after t periods is calculated as

$$R_{P,t} = Q_t \bullet R' \tag{7}$$

where

$$R' = \begin{bmatrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{bmatrix} \tag{8}$$

When the process is used to simulate deterioration, the following condition applies:

$$p_{i,j} = 0 \text{ for } i > j \tag{9}$$

This is because the condition of a deteriorating element cannot return to a previous state (a better condition) without external intervention. Therefore, the probability of an element returning to a previous condition is always zero. When an element reaches its worst state (failure state), the following condition applies:

$$p_{m,m} = 1 \tag{10}$$

This indicates the element has deteriorated to the point of failure and will remain in that state. Consequently, the general form of the transition probability matrix for a deteriorating element is defined as

$$P = \begin{bmatrix} p_{1,1} & p_{1,2} & p_{1,3} & \cdots & p_{1,m} \\ 0 & p_{2,2} & p_{2,3} & \cdots & p_{2,m} \\ 0 & 0 & p_{3,3} & \cdots & p_{3,m} \\ \vdots & \vdots & \vdots & & \vdots \\ 0 & 0 & 0 & \cdots & 1 \end{bmatrix} \tag{11}$$

A further restriction allowing the condition to deteriorate by no more than one state in one rating cycle is commonly used in the deterioration modeling. The transition probability matrix is then denoted as

$$P = \begin{bmatrix} p_{1,1} & p_{1,2} & 0 & \cdots & 0 \\ 0 & p_{2,2} & p_{2,3} & \cdots & 0 \\ 0 & 0 & p_{3,3} & \cdots & 0 \\ \vdots & \vdots & \vdots & & \vdots \\ 0 & 0 & 0 & \cdots & 1 \end{bmatrix} \tag{12}$$

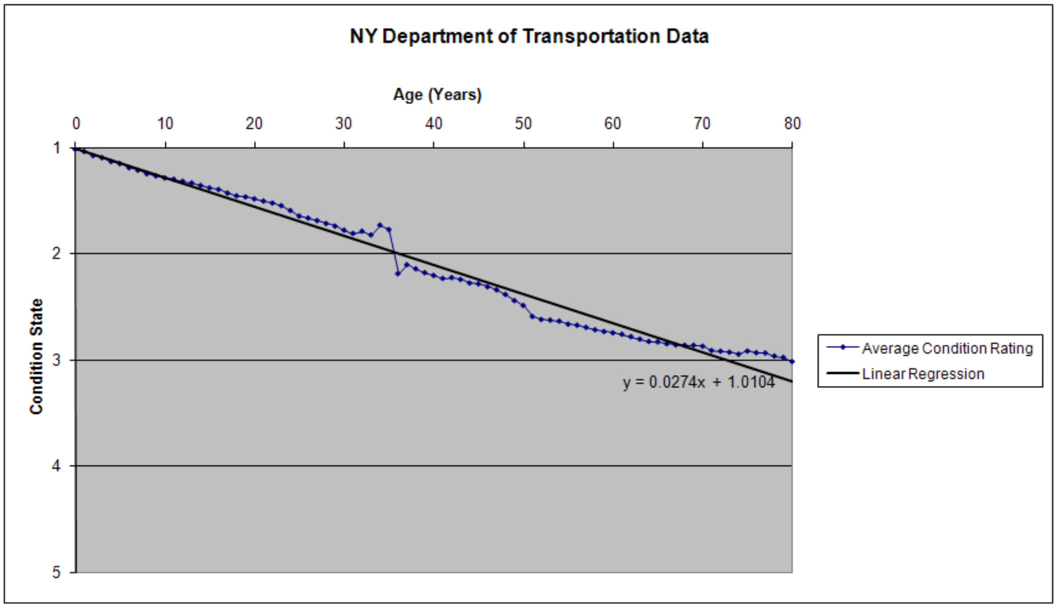
However, some SHS inspection reports have shown that the structure has changed by more than one state during the inspection period; therefore, the transition probability matrix defined in Equation 11 may better fit actual inspection data.

Derivation of Transition Probabilities:

There are several methods for deriving a transition probability matrix. The methods include expert opinion, linear regression, and Poisson regression (Madanat et al. 1995). Since the available data containing condition states are limited for navigation structures, the development of a probabilistic method that can be updated as data becomes available is proposed. The main goal is to develop a method which can be verified as actual data becomes available. This will allow the method to be used confidently to predict future deterioration of hydraulic steel structures. The data used in the development of this method was provided by the New York State Department of Transportation. This data was used not only because it was accessible but also because it represents condition state data of thousands of steel bridge elements over a period of eighty years of inspections.

Additionally, steel bridge element deterioration is caused by the same effects that cause the deterioration of navigation structures (loss of protective system, corrosion, cracking and fatigue, impact, and overloads). The data used is shown in Figure 15.

Figure 15. Condition State Data from the New York Department of Transportation.



Fluctuations in the data, as can be seen between 30 and 40 years, occur because the data represent the average condition state of many elements. To eliminate the fluctuations and make the data more manageable, a linear regression equation was calculated as

$$y = 0.0274x + 1.0104 \tag{13}$$

where x is the age in years and y is the condition state.

Condition state values at ten-year intervals were calculated using Equation (13). The calculated values were used as the average condition state at each interval. Using Weibull distribution and Latin Hypercube Simulation (LHS), synthetic random condition state values were generated to represent a range of condition states at each ten-year interval. Weibull distribution parameters for each interval were chosen to yield approximately the same average values represented in Figure 15.

Figure 16 shows the synthetic values (vertical points) generated to simulate a range of condition states at each ten-year interval. One-thousand random values were generated at each interval. The diagonal line crosses through the average value of each ten-year interval.

Figure 16. Synthetic Condition State Values.

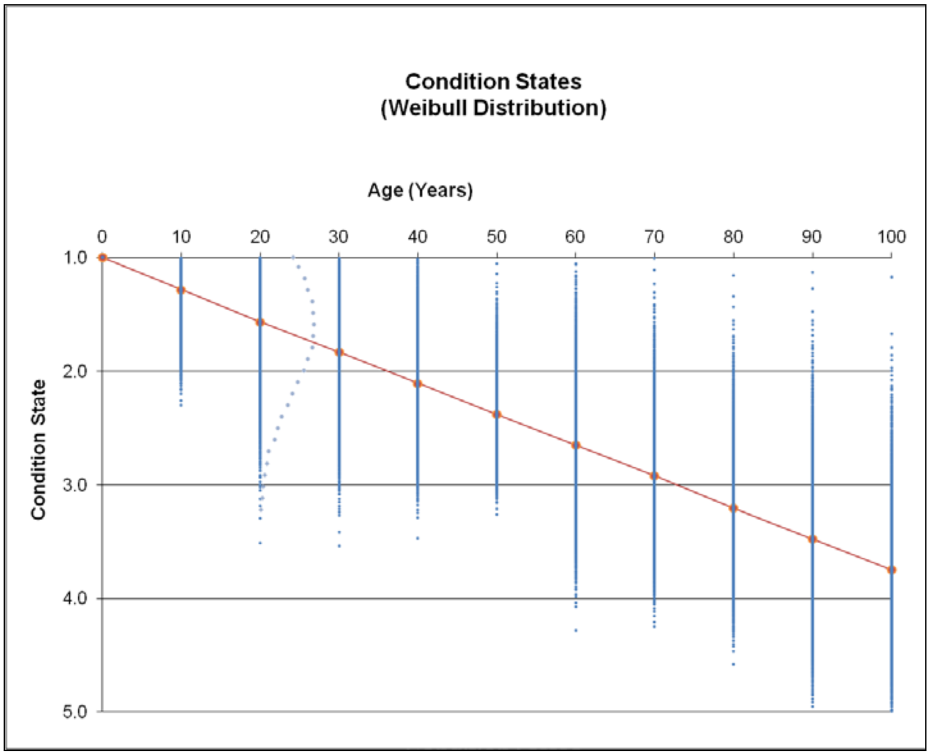
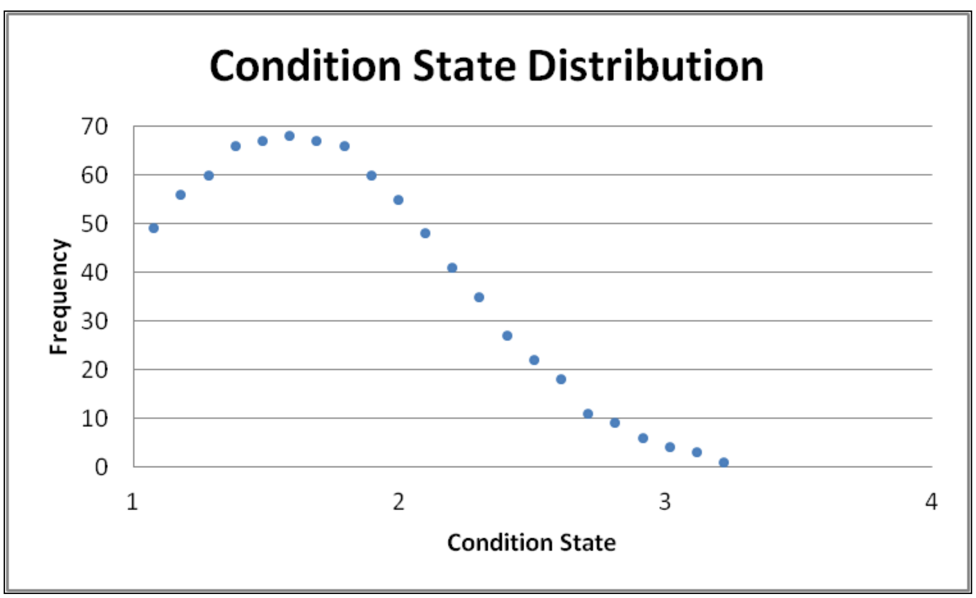


Figure 17 shows the distribution of values generated for the 20-year interval. These values are also superimposed in Figure 16. Similar distributions of values were generated for each of the other intervals.

Figure 17. Distribution of Condition State Values generated for a 20-year Interval.



Using the generated condition state values for each interval, the transition probabilities were calculated as

$$p_{i,j} = \frac{N_{i,j}}{N_i} \tag{14}$$

Where $N_{i,j}$ is the number of elements that change from condition i to condition j after one interval, and N_i is the number of elements that were in condition i in the previous interval.

The transition probability values are shown in Table 2.

Table 2: Transition Probabilities.

Condition State	1	2	3	4	5
1	0.973	0.027			
2		0.972	0.028		
3			0.972	0.028	
4				0.973	0.027
5					1.000

Applying Markov chain:

$$P = \begin{bmatrix} 0.973 & 0.027 & 0 & 0 & 0 \\ 0 & 0.972 & 0.028 & 0 & 0 \\ 0 & 0 & 0.972 & 0.028 & 0 \\ 0 & 0 & 0 & 0.973 & 0.027 \\ 0 & 0 & 0 & 0 & 1.000 \end{bmatrix} \tag{15}$$

The initial state for a new element is expressed as

$$Q_0 = [1,0,0,0,0] \tag{16}$$

The condition vector is

$$R = \begin{bmatrix} 1 & 2 & 3 & 4 & 5 \end{bmatrix} \tag{17}$$

Now to calculate the condition rating at the next rating cycle (t = 2), applying Markov chain we have

$$P_2 = P^2 \tag{18}$$

$$P^2 = \begin{bmatrix} 0.9469 & 0.0524 & 0.0007 & 0 & 0 \\ 0 & 0.9456 & 0.0536 & 0.0008 & 0 \\ 0 & 0 & 0.9447 & 0.0545 & 0.0008 \\ 0 & 0 & 0 & 0.9460 & 0.0540 \\ 0 & 0 & 0 & 0 & 1.0000 \end{bmatrix} \tag{19}$$

Applying Equation (5), vector Q_t, representing the condition state after two periods is calculated as

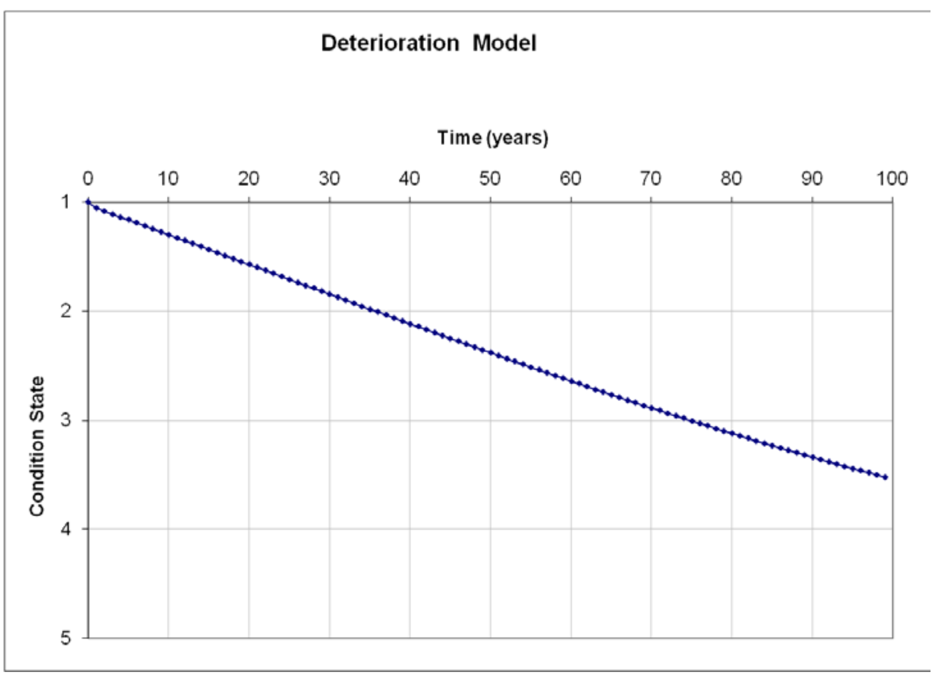
$$Q_2 = Q_0 \bullet P^2 = \begin{bmatrix} 0.9469 & 0.0524 & 0.0007 & 0 & 0 \end{bmatrix} \tag{20}$$

and the condition, using Equation (7) is calculated as

$$R_{P,2} = Q_2 \bullet R' = 1.0539 \tag{21}$$

Continuing in a similar fashion, the rest of the deterioration curve shown in Figure 18 was calculated.

Figure 18. A Markov chain deterioration model.



4 US Army Corps of Engineers Navigation Structures Inventory Management System (NAVSIMS) User's Manual

The NAVSIMS JavaScript/EXTjs web application is a tool to file inspections on navigation steel structures. The tool consists of an overhead map containing all the locks and dams in the United States. Each project has been associated with the Division and District responsible for their maintenance and operation. Each project is identified with markers which allow the user to easily associate inspections, files, and other data with a structure. NAVSIMS is capable of calculating and predicting the future condition of the navigation steel structure over spans of time. This information can be visualized via a graphing tool that displays the deterioration curves and develops an inspection report.

Requirements

To run NAVSIMS web based program it will require the following:

a. A control access card (CAC)
b. Internet connection
c. Internet Explorer

Getting Started

The first step is to lunch internet explorer and type https://navsims.usace.army.mil/ to lunch the program. The user will login into the program by inserting the CAC card into the CAC card reader and typing the code. Ensure that you enter **https** and **not** http. The web page is not reachable with http.

Visual Overview

The NAVSIMS interface has been develop to facilitate the navigation of the program and it consists of two primary steps: the selection of the location of a lock or dam; and the filing of the inspection forms and uploading files associated with the inspection and/or project.

Program Description

The **NavSim Navigator** provides a region based, hierarchal tree listing of available locks and dams (Figure 19). **Sites** are grouped by their **Districts**. Districts are grouped by **Divisions**. A listing of **Divisions** can be located under the **NavSim Navigator** tab (Figure 20).

Figure 19. Example of the NAVSIMS main window.

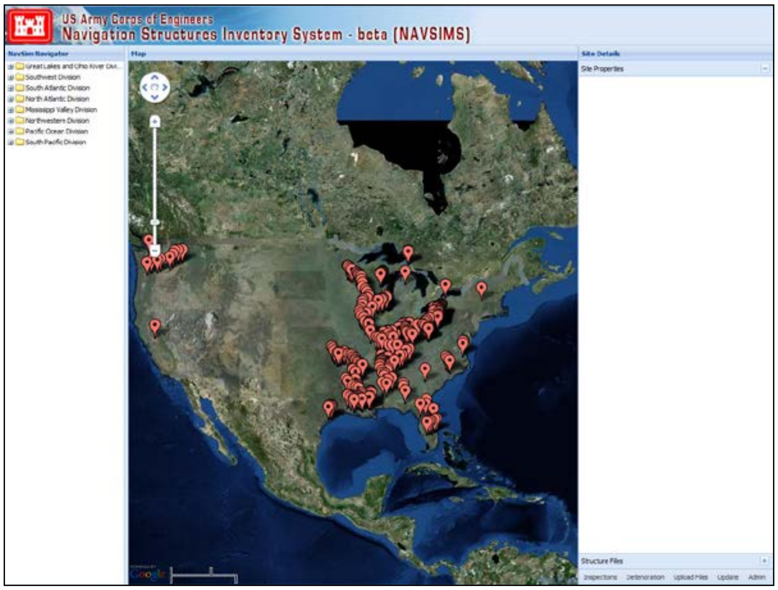
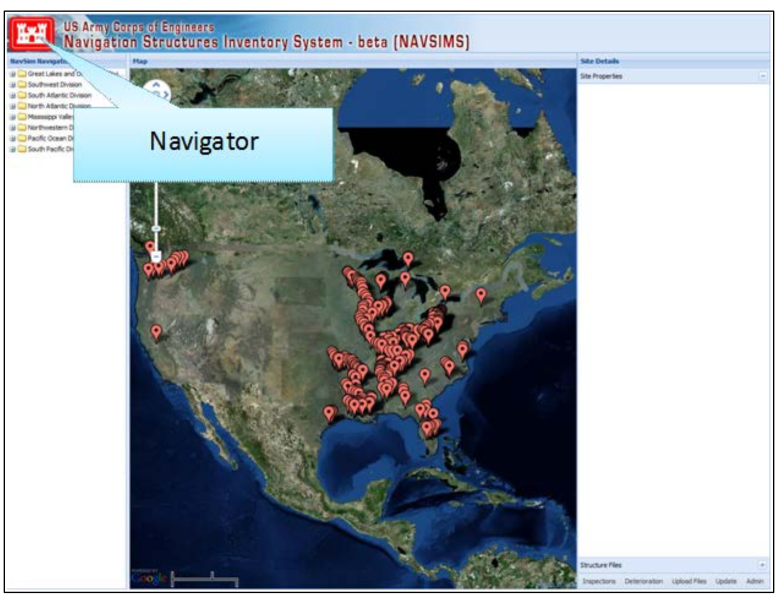


Figure 20. Main window showing gates grouped by Divisions and Districts.



The **Map** tab allows the user to view the location of a structure. The site can be chosen by clicking on the tab on the map that corresponds to the structure that the inspection will be filed in. When a **Site** is selected; that sites details are presented in the **Site Details Panel** (Figure 22).

Figure 21. Main window showing the USA map with the location of all Locks.

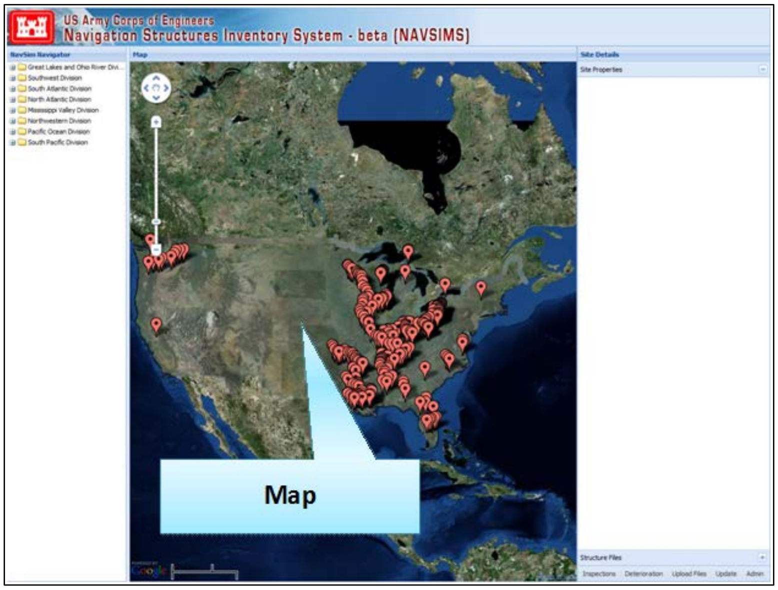


Figure 22. Main window showing the area where details of the selected location will be displayed.

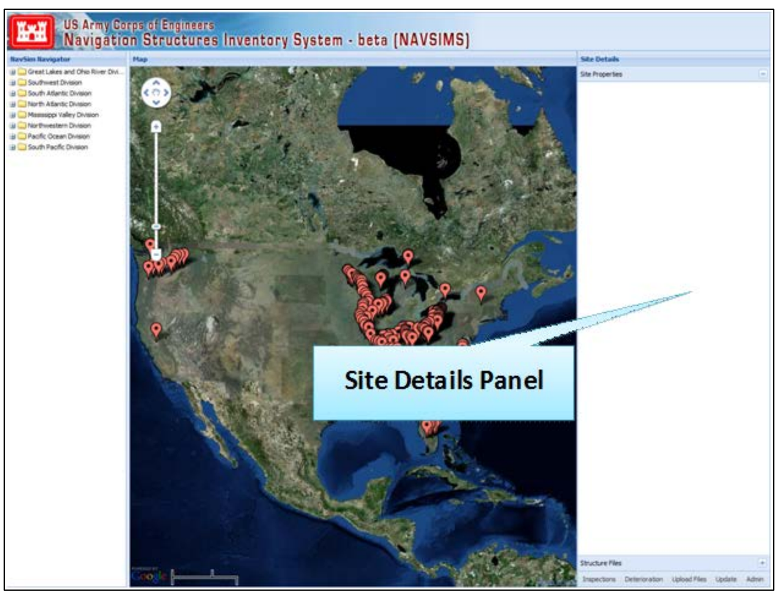
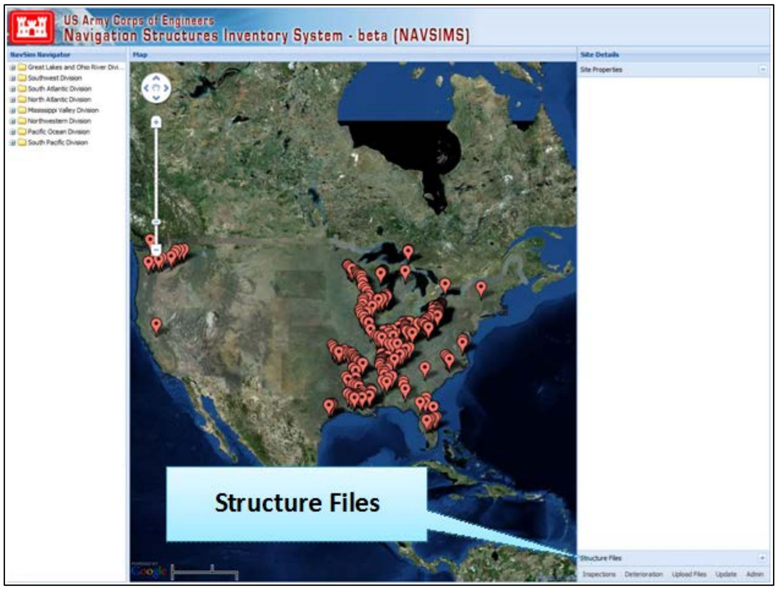


Figure 23 shows the tab required to upload files such as pictures, CAD drawings, numerical simulation input files, design memorandums, previous inspections reports, etc. The files need to be associated with a specific site and then with an inspection. This option is under the **Structure Files** tab at the bottom right side of the viewing window.

Figure 23. Main window showing the location of the tabs required to input the inspection data.



Selecting a Site

In the **NavSim Navigator** tab there is a listing of Divisions. To select a site, direct your cursor over the Divisions until the Division you choose is highlighted, left click on the selected Division in the **NavSim Navigator** tab (Figure 24). Districts under a Division will be shown. Select a District by left clicking on it (Figure 25). Sites in the selected District will be shown. Select a site by left clicking on it (Figure 26).

Site Details

When a site is selected, information about the site will show up in the **Site Details** panel on the right-hand side of the screen (Figure 27).

A Marker representing the site location will be shown in the center of the map. The marker corresponds to the latitude and longitude coordinates of the site. If you click on another marker on the map (select another site) the **NavSim Navigator** and **Site Detail** information will update to reflect the change of site (Figure 28).

Left clicking on the **Structure Files,** located at the bottom of the **Site Details** panel, will allow for the user to view and download files associated with the chosen site. To download a file, click the name of the file underlined and in blue to download it (Figure 29).

Figure 24. In this example, the Mississippi Valley Division is selected.

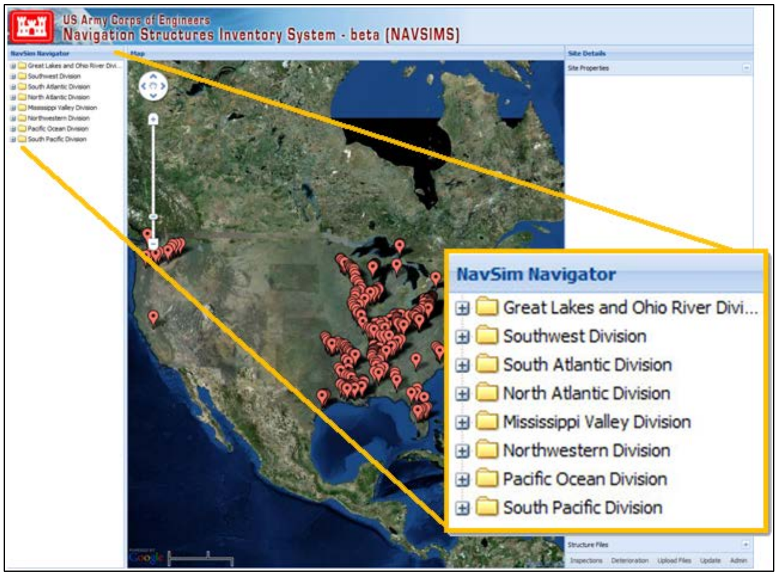


Figure 25. In this example, the St. Paul District is selected.

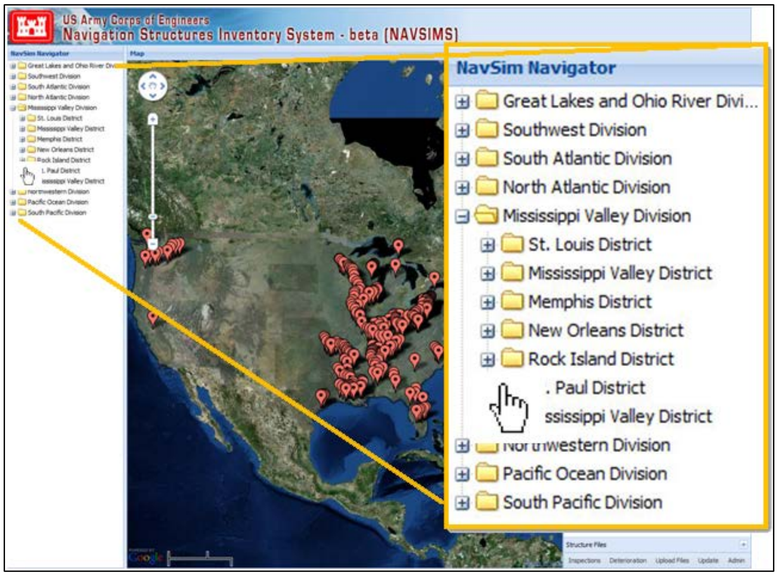


Figure 26. In this example, the Lock & Dam 10 is selected.

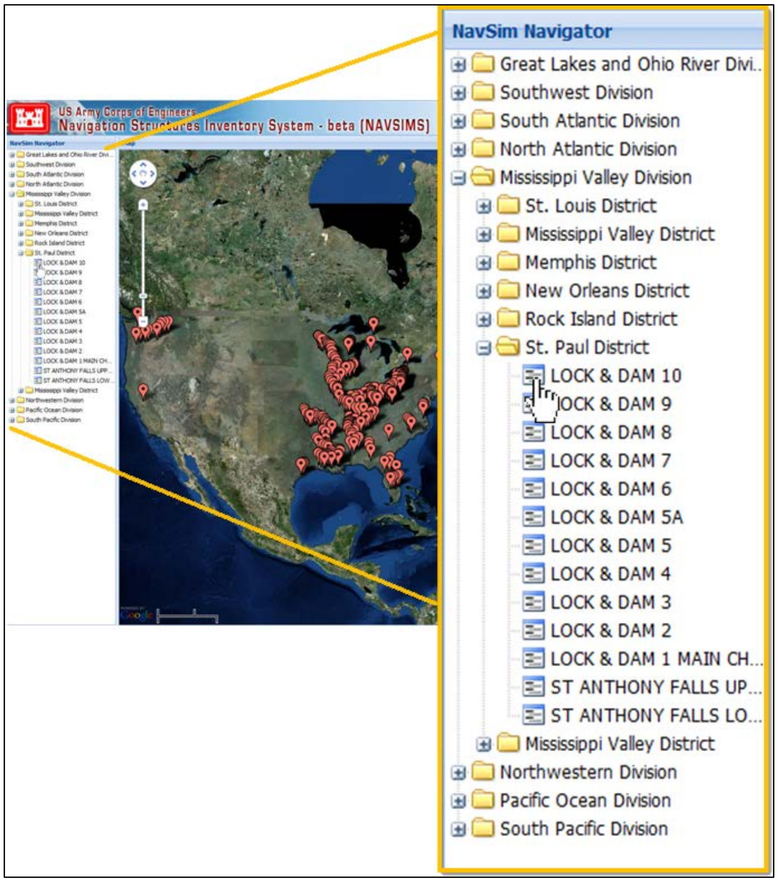


Figure 27. Detail area showing the information of the selected lock (Lock 10).

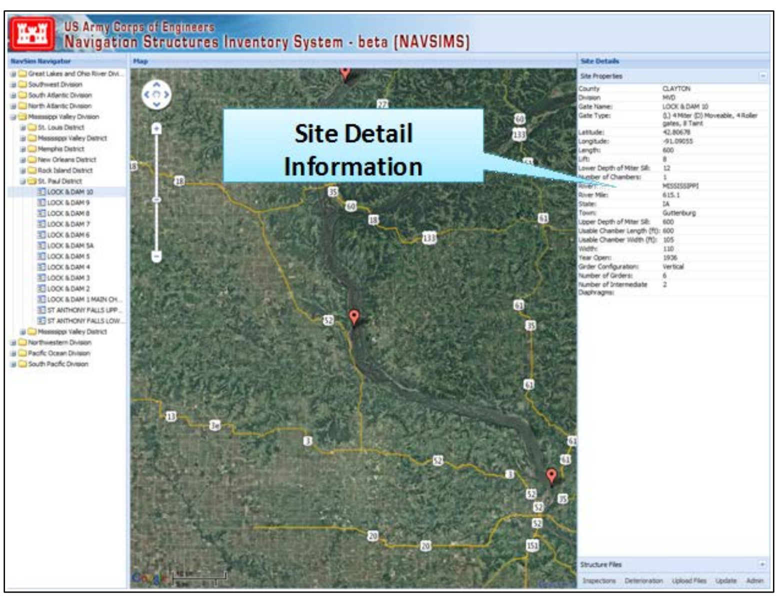


Figure 28. Main window showing a close up location of the selected site.

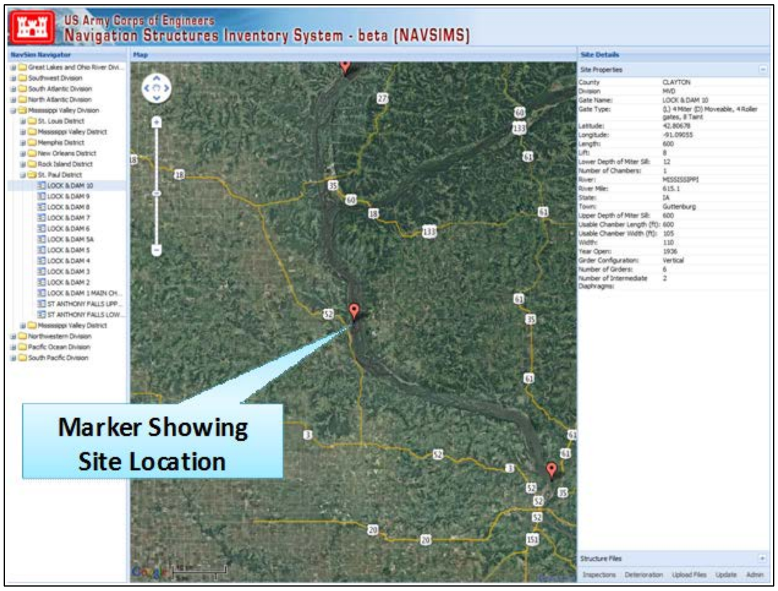
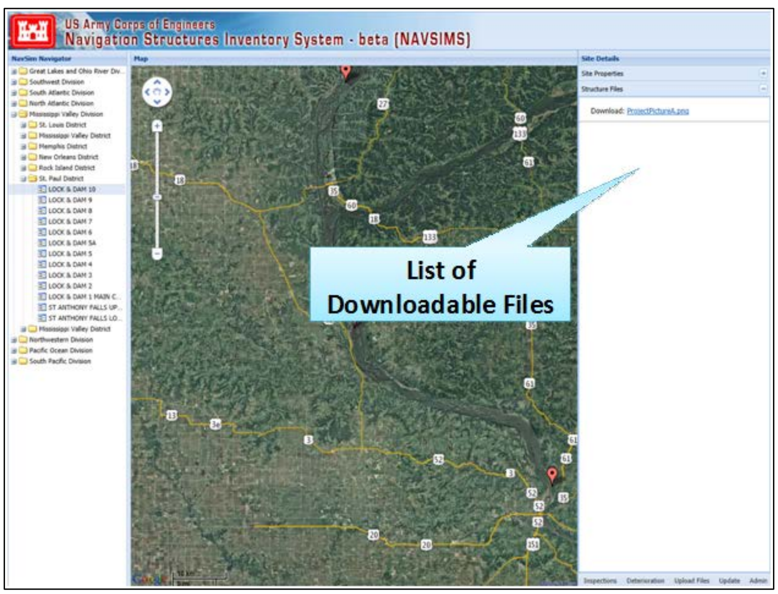


Figure 29. List of Downloadable Files.



Control Panel

The control panel shown in Figures 30 and 31 contains several buttons used to launch tools. These tools are used to associate inspections, users, and files with a selected site. The control panel is located under the **Structure Files** tab.

Figure 30. Location of Control Panel tab used to launch tools associated with the inspection.

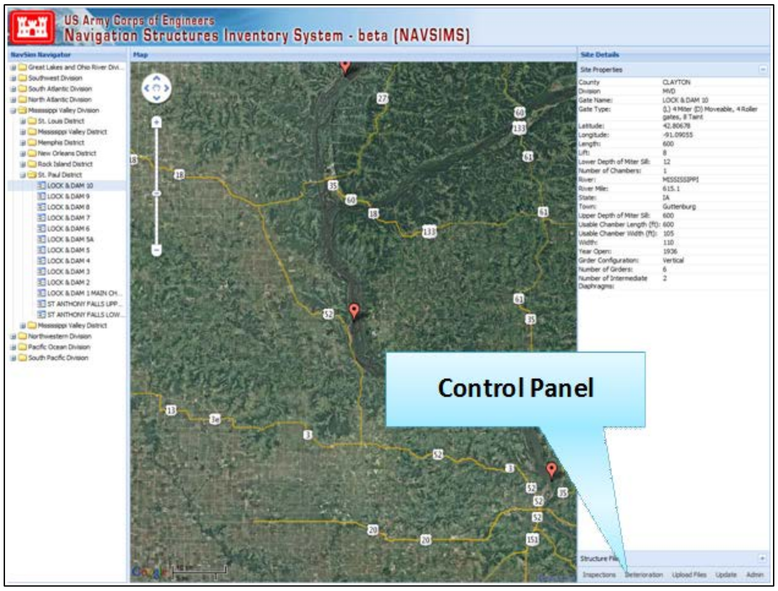


Figure 31. Example of the Control Panel.

The control panel consists of **Update**, **Inspections**, **Deterioration**, **Uploaded Files**, and **Admin** tabs. The following gives a brief overview of each tab:

1. The **Inspections** tab displays a window containing a tool for the creation and viewing of existing inspections associated with a chosen site.
2. The **Deterioration** tab will display the deterioration graphs for a chosen site.
3. The **Uploaded Files** tab displays a window containing a tool for the association of files (e.g., CAD drawings) with a site.
4. The **Update** tab displays a window containing a tool for the updating of Girder count, Intermediate Diaphragm count, and site configuration.
5. The **Admin** tab displays a window containing a tool for associating users with divisions and removing users.

Updating Site Details

The user may change/update the Girder and Intermediate Diaphragm count along with the configuration (Vertical or Horizontal) by pressing the **Update** tab on the **Control Panel** (Figure 32).

When satisfied with the changes, press **Save** to finalize the changes to the site details (Figure 33).

Pressing **Cancel** will discard any changed values and the site details will not be affected.

Figure 32. Update tab on the Control Panel used to update the number of horizontal girders and intermediate diaphragms.

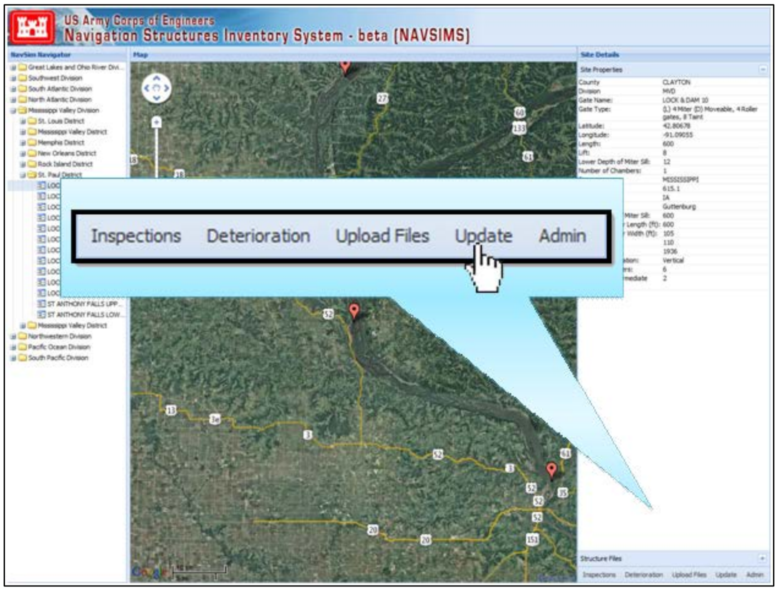
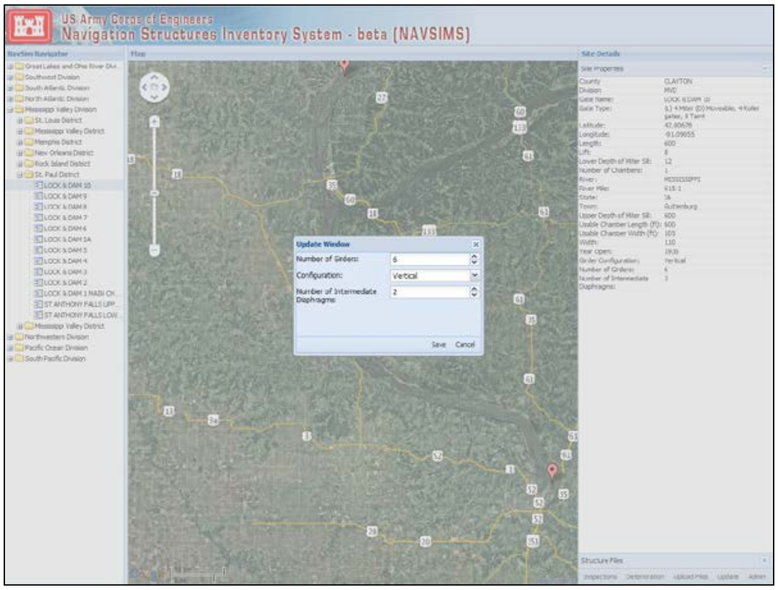


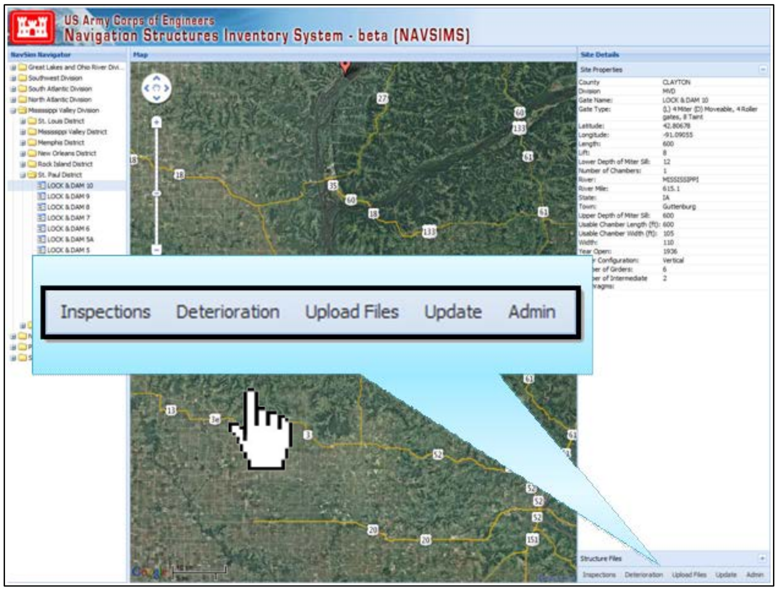
Figure 33. Update window.



Inspections

Press the **Inspections** tab to launch the Inspections Wizard (Figure 34). A site can have many inspections**,** which consist of an Inspection Form, Element Inspections, and Inspection Files.

Figure 34. Example of the inspection tab.



An Inspection Form (Figure 35) is a virtual recreation of an in-the-field inspection form (Sauser and Riveros 2010). The Inspection forms, as described by Sauser and Riveros, provides a systematic approach to identifying, documenting, and tracking deficiencies in HSS, a means to predict useful performance, and a tool to predict the future condition for prioritizing maintenance and replacement funding. It is not necessary to complete all fields in order to save the form.

To Save the entered information the user can press the **Save** button located at the botton rightside corner of the form to save it along with the form at any time (Figure 36). Additionally, The user may at any time start a new and empty form by pressing the **New** button (Figure 37).

Any existing inspection that has been saved appears in the List of Inspections in the left panel under **Inspections**. It may be viewed by all users and only edited by the inspector at any time by left clicking on the date in the List.

Figure 35. Example of the inspection form.

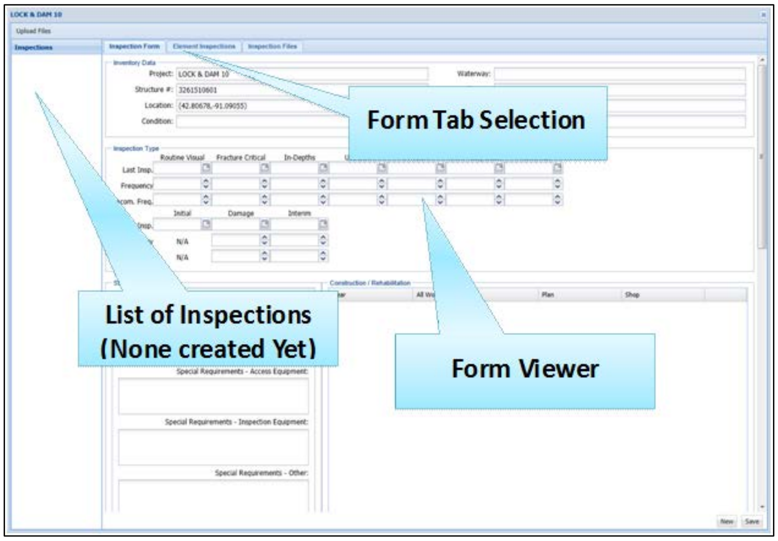


Figure 36. Inspection Form showing the location of the New and Save buttons.

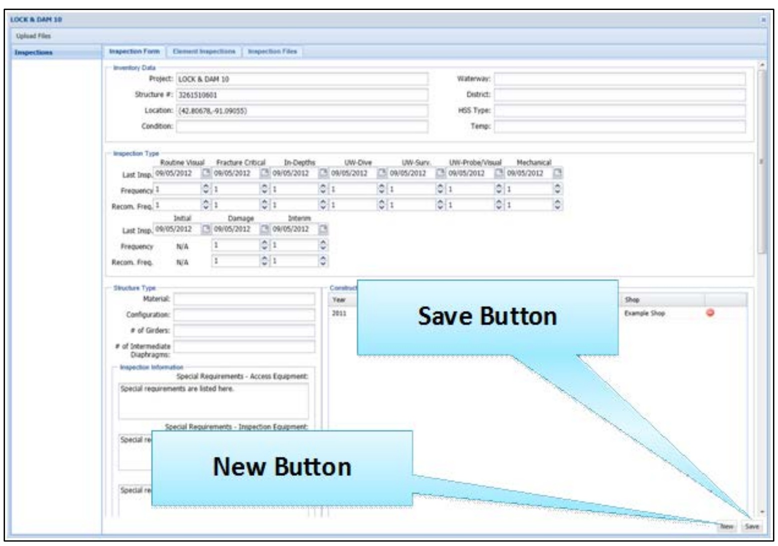
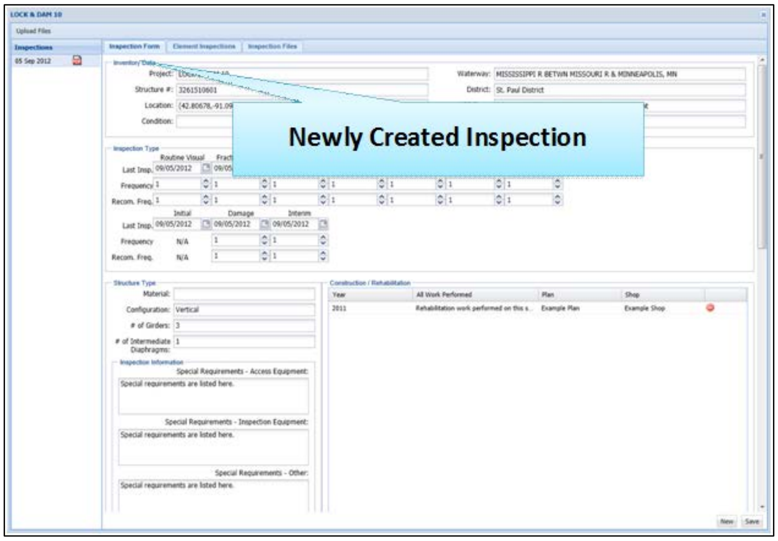


Figure 37. Example of a New Inspection Form.



Element Inspection

To create an element inspection, start by clicking on the **Element Inspections** tab (Figure 38). An Element Inspections Form will appear in the Form Viewer.

Fill out Element Inspections with the data collected on the field. Note that the state fields will only accept numeric input. Press the **Save** button when finished or press the **New** button for an empty Element Inspections form (Figure 39).

Figure 38. Indicator showing the location of the Element Inspections tab.

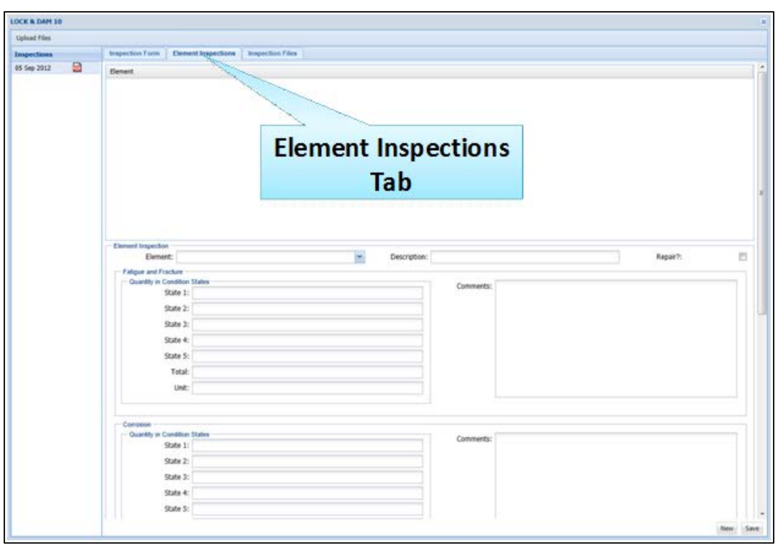
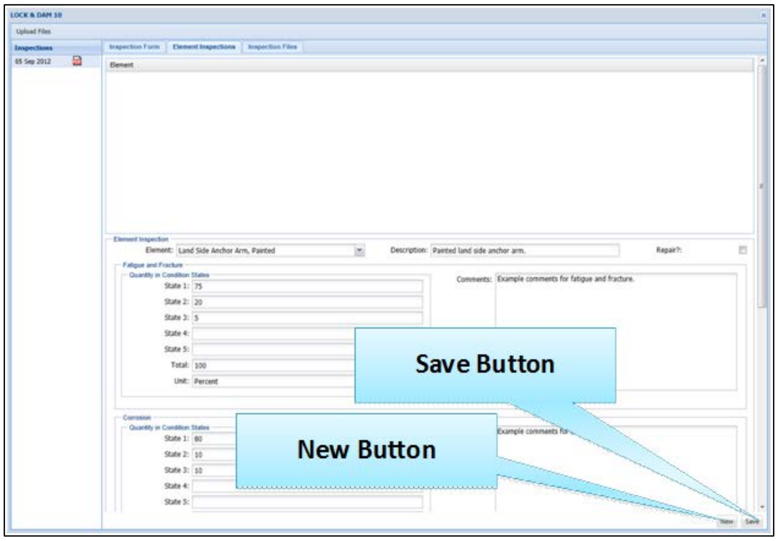


Figure 39. Indicators showing the location of the New and Save buttons.



Inspection Files

Your saved elements will appear in the **Element List**, located in the **Inspection Files** tab of the toolbar (Figure 40). An **Element** may be viewed and edited by selecting it. However, they may only be modified by the inspector.

Files may also be associated with an individual inspection (different from associating a file with a site). To associate a file with an inspection, first click on the **Inspection Files** tab (Figure 41).

Figure 40. Indicator showing which tab to find the Element List.

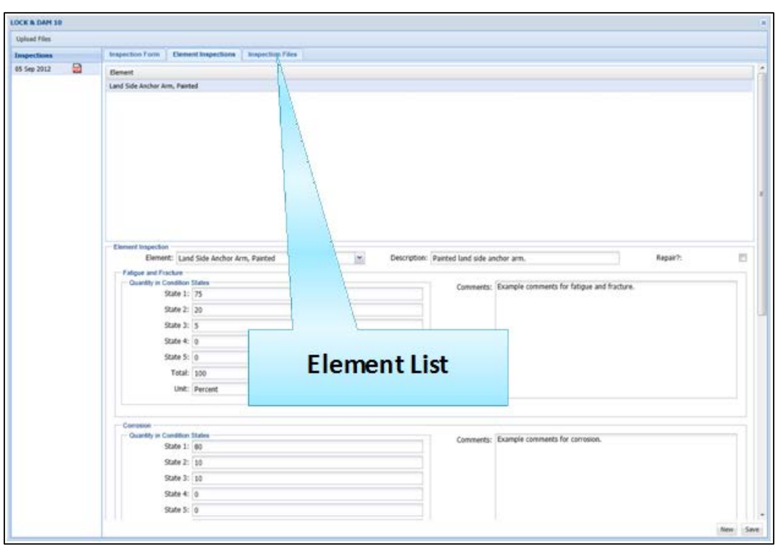
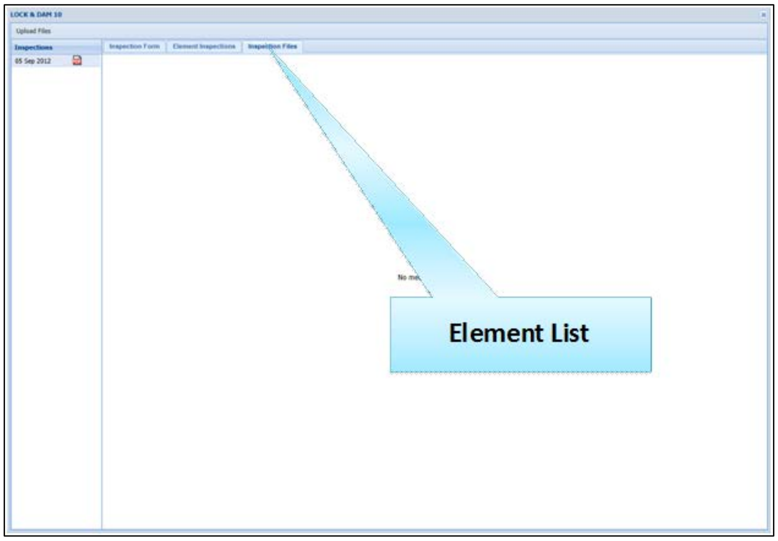


Figure 41. Method to associate a file with an inspection.



To display the File Wizard, click on the **Upload Files** tab. The wizard will appear on the screen for uploading the file (Figure 42).

When associating a file with an inspection, you must first select the **file type** to be associated before proceeding. Select a file type from the dropdown menu selection shown in Figure 43.

With a file type selected, you may now browse your computer to select a file of that type to be associated with the inspection. To browse the files in your computer, the **Browse** button must be clicked (Figure 44).

Figure 42. Location of the Upload Files button.

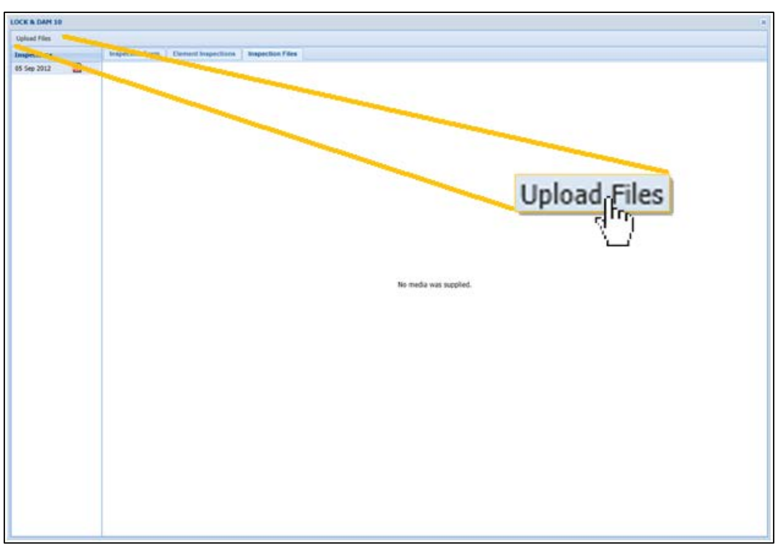


Figure 43. Example of the dropdown for the selection of the file type.

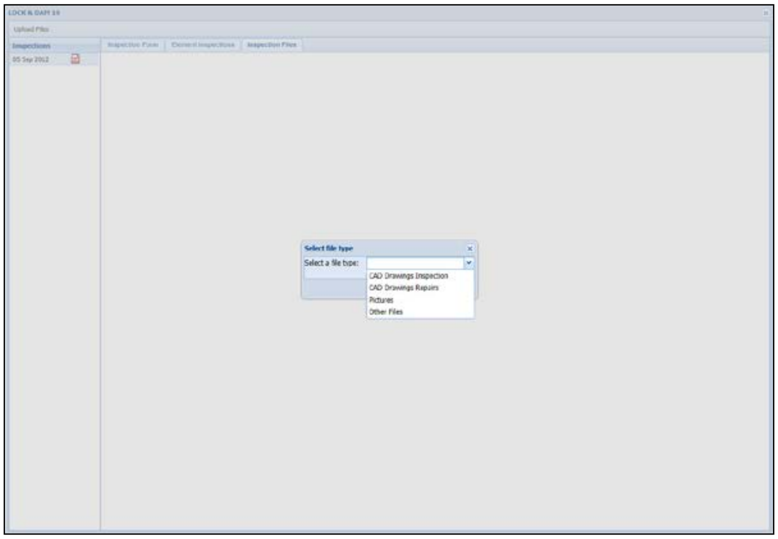
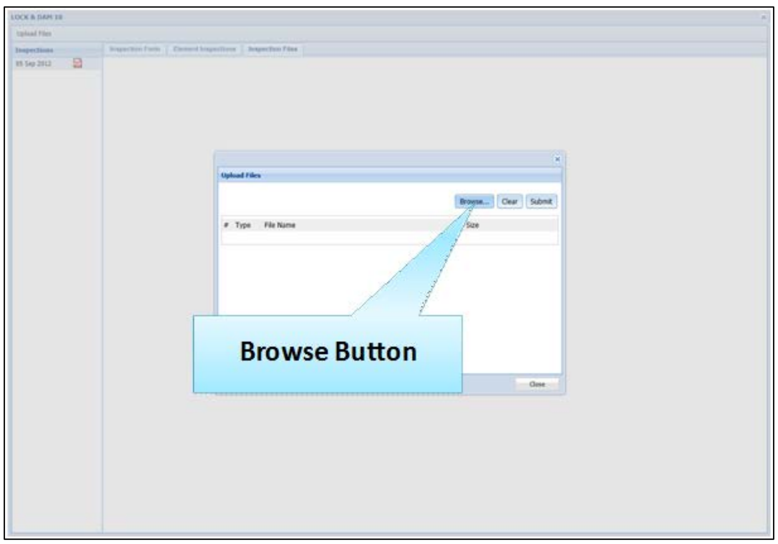


Figure 44. Indicator showing the location of the Browse button.



A file selection window (Figure 45) will appear showing your computer's file structure. Please locate the folder of the file you wish to associate with the inspection, left click on the file, and then press open. It is important to ensure the selection of the appropriate file to associate. If it is a CAD type drawing you will want to associate only image files with it (.jpeg, .png, etc.)

Your selected file will appear for your review before being submitted. To submit the file and finalize its association with the inspection, press the **Submit** button (Figure 46). If the wrong file has been chosen, the **Clear** button can be used to clear the file or list of files to upload.

Figure 45. Example of the location of the selected file to be uploaded.

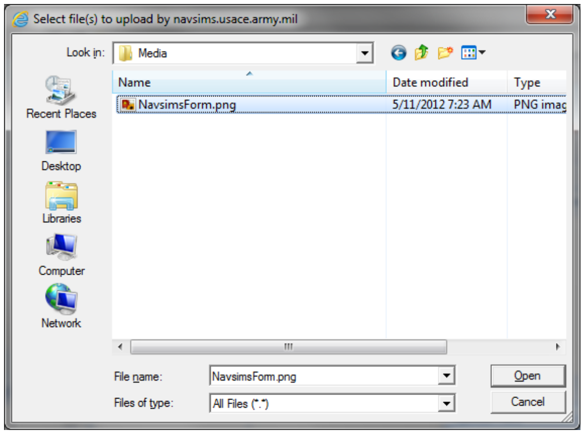
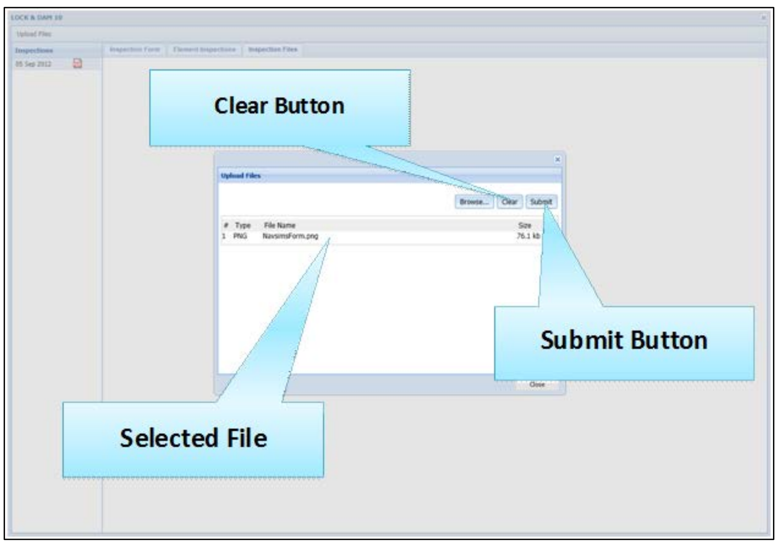


Figure 46. Indicators showing how to clear or submit a selected file.



Inspection Exporting to PDF

An inspection can be exported as a report. The report is in the form of an Adobe PDF file. To export an inspection report press the **PDF Export** symbol located to the right of the date of an inspection under the **Inspections** tab (Figure 47).

Viewing Deterioration Graphs

To view Deterioration Graphs, click the **Deterioration** tab in the bottom right side of the screen (Figure 48). A window will pop up with nothing in it (Figure 49). To view a list of elements to graph, press the **Type** List dropdown button. This will list the Elements available to plot the deterioration curves (Figure 50).

Figure 47. Indicator showing how to select an inspection.

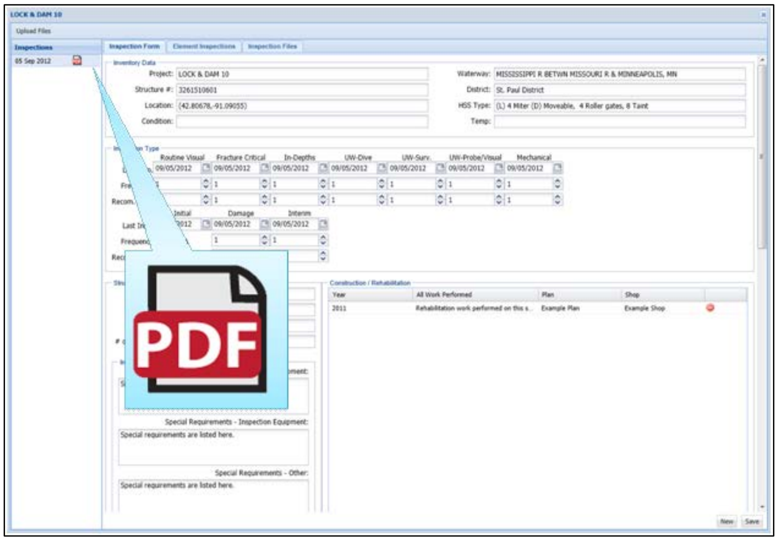


Figure 48. Location of the Deterioration tab in the Control Panel.

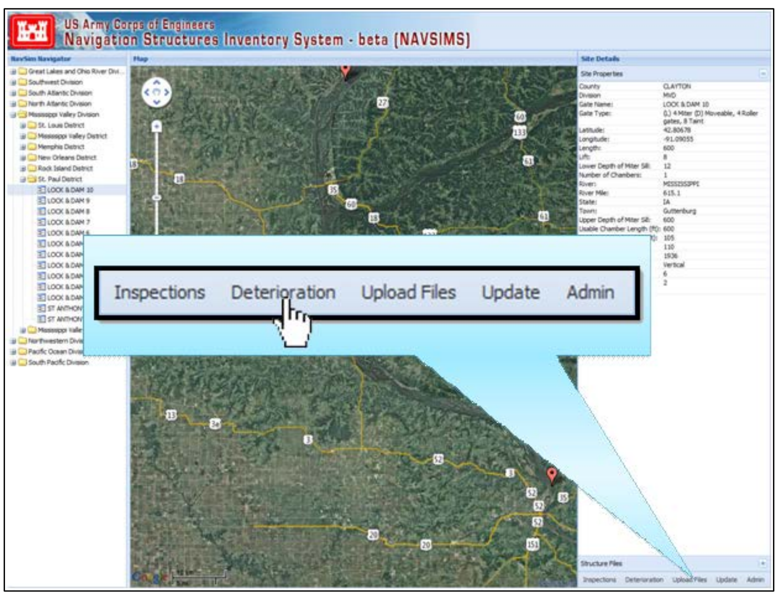


Figure 49. Location of the dropdown for the Type list.

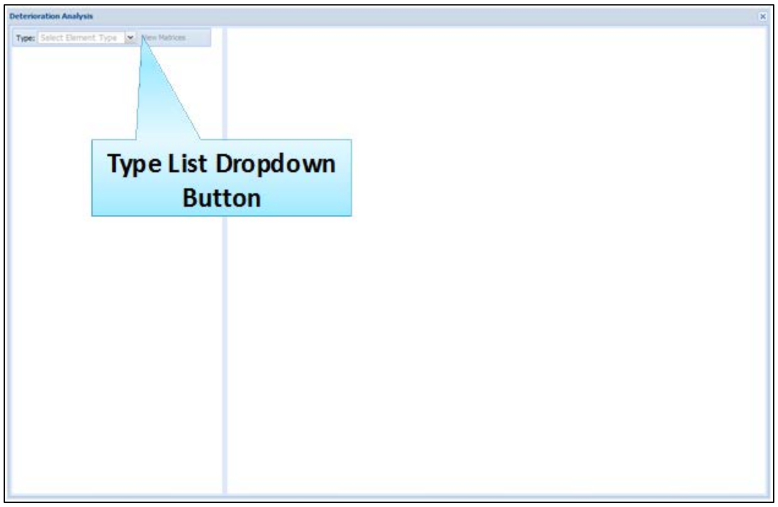
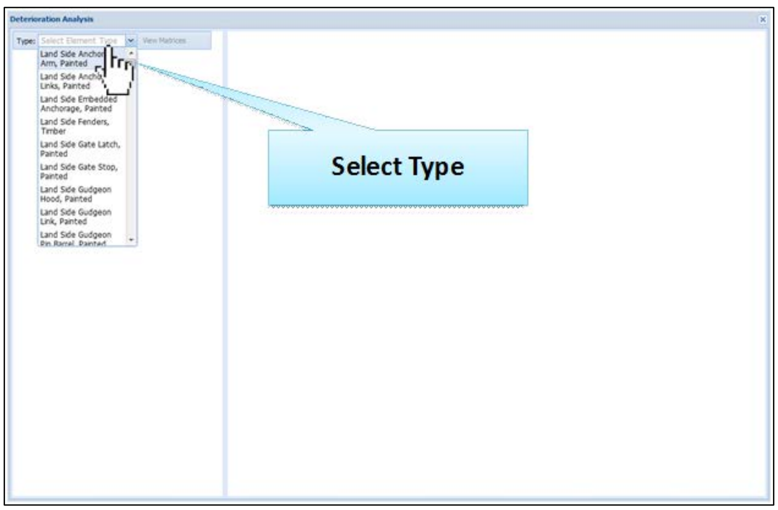


Figure 50. Selection of the Type of deterioration curve.



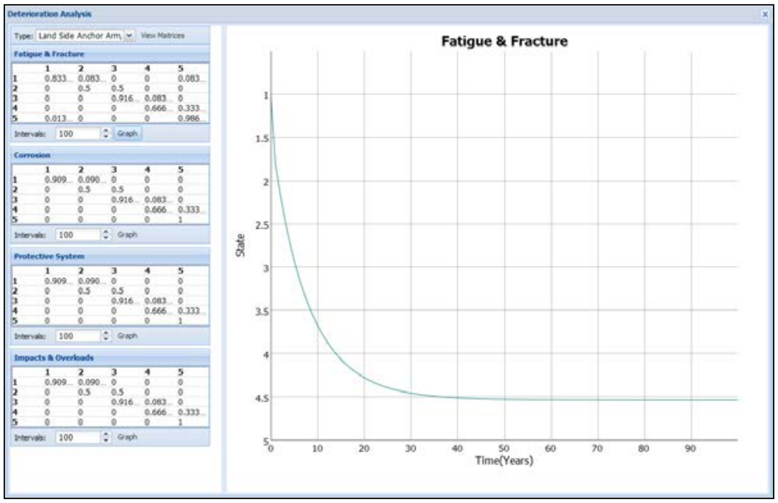
Next select a type from the list that appears. As seen in Figure 50, the **Land Side Anchor Arm, Painted** is selected. After the selection is made, the viewer can observe the deterioration curve for the Element type.

The graph will appear on the right with the title of the deterioration that is being plotted. The *y*-axis represents the condition state (1-5) and the *x*-axis represents time in years for the desired time interval.

To graph another matrix, simply press the **graph** button on the corresponding matrix panel (Figure 51).

To change the type, simply repeat the type selection and press **View Matrices**.

Figure 51. Example of Deterioration curve.



Associating Files with Site

Just as a file can be uploaded and associated with an inspection of a site, so too can a file be uploaded and associated with an entire site (and subsequently downloaded by others).

To associate a file with a site, begin by clicking the **Uploaded Files** button on the **Control Panel** (Figure 52). The subsequent steps for uploading the file are the same as detailed in the **Inspection Files** section. Uploaded files associated with a site will appear in the **List of Downloadable Files** under the **Structure Files** tab (Figure 53).

Figure 52. Location of the Upload Files tab in the toolbar.

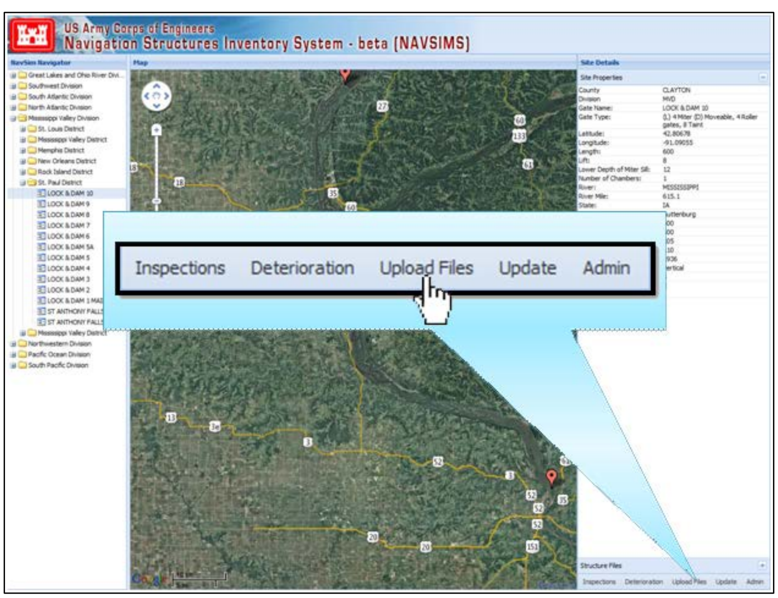
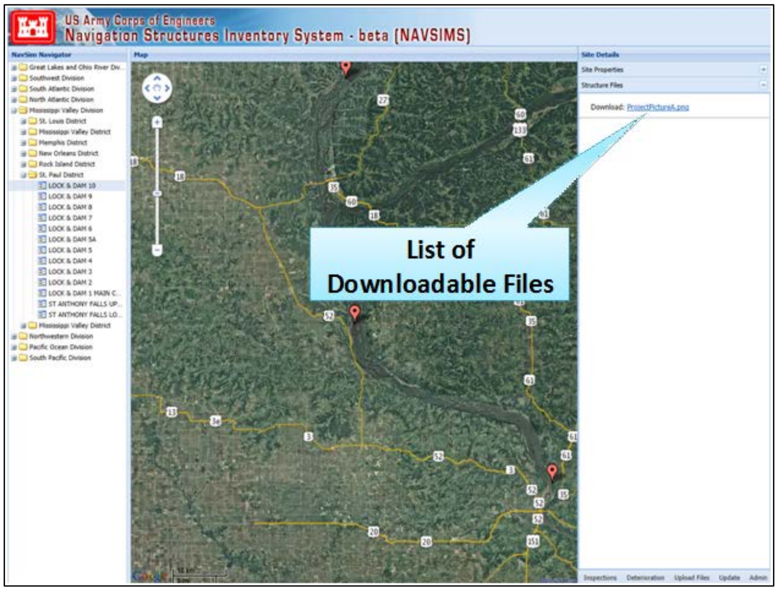


Figure 53. Location of the List of Downloadable Files.



Administration

If a user is an administrator the **Admin** tab will be visible on the **Control Panel**. Pressing the **Admin** tab will launch a wizard which will allow the user to associate users (including the current user) with Districts (Figure 54). The changes are not reflected until the webpage is refreshed. On the Administration window, a list of available users will be presented. These are users who may be assigned to a District (Figure 55). To assign a user to a District, first left click on the user's certificate name in the row and then press the **Assign Inspector** button (Figure 56). A prompt window will appear requesting the user to select an Entity (District). Please select the District in which the Inspector will be assigned (Figure 57). Press **Ok** when finished.

The **Entity Inspectors** tab will automatically be selected to show and confirm the currently assigned user (the row of the assigned user will be highlighted blue). To remove a user or any other user from assignments to Districts, select the user's row and press the **Delete Inspector** button (Figure 58). The **Assign User Request** button will change any selected users whose approval status is false to true (Figure 59).

Figure 54. Location of the Admin tab in the toolbar.

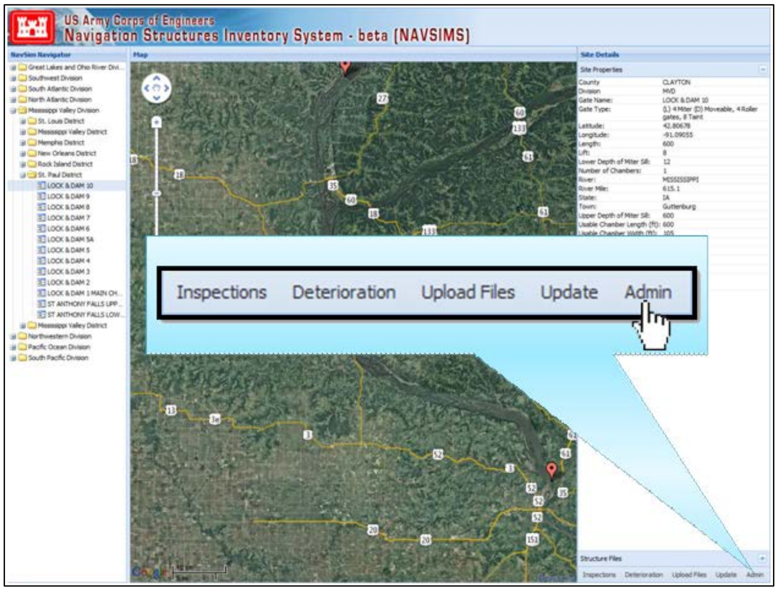


Figure 55. example of the List of Available users.

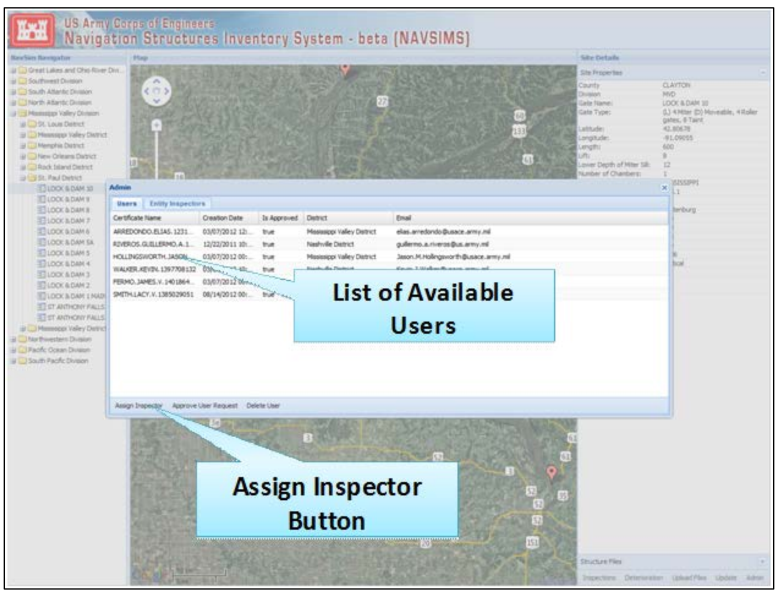


Figure 56. Location of the Assign Inspector button.

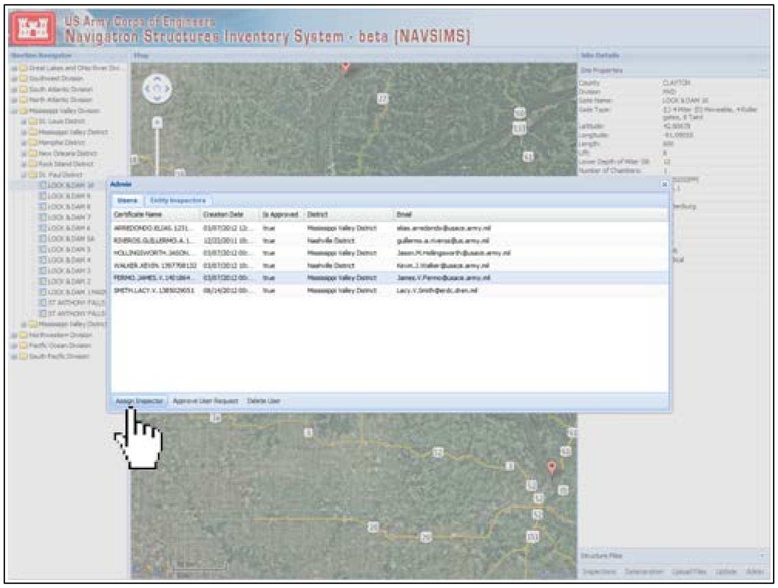


Figure 57. Example of the dropdown for the Entities (Districts).

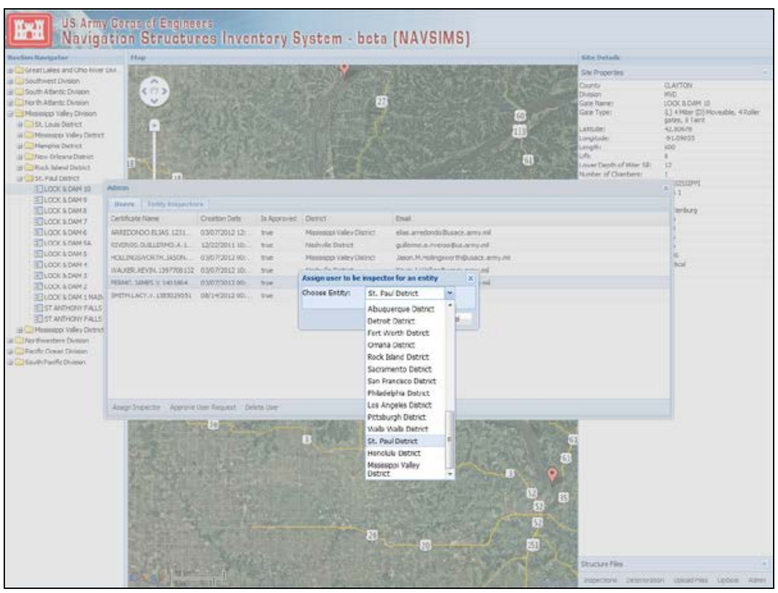


Figure 58. Location of the Delete Inspector button.

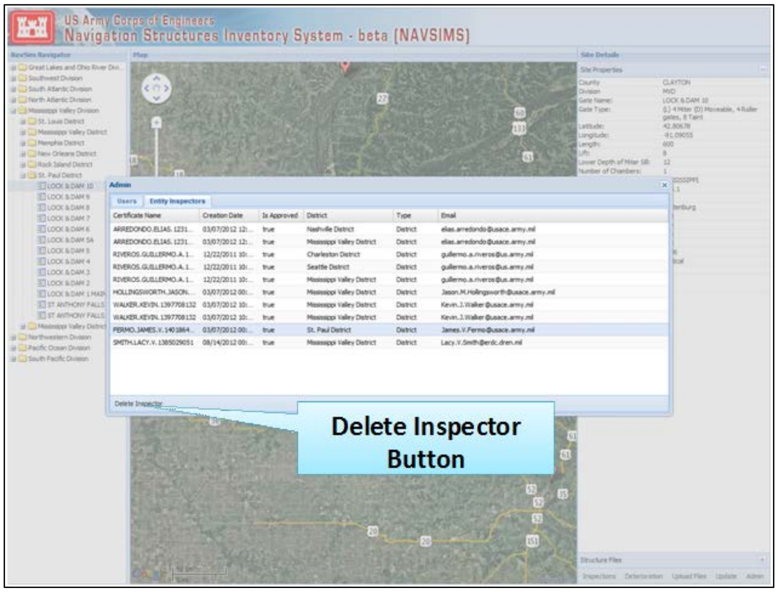
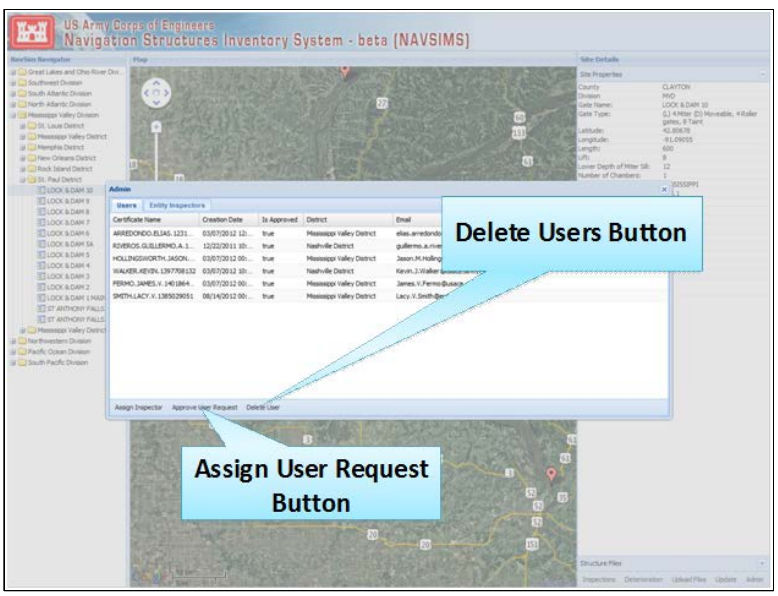


Figure 59. Location of the Assign User Request and Delete Users buttons.



5 Conclusions and Recommendations

The application of the Markov chain provides navigation structures' managers a powerful and convenient tool for estimating the navigation structure's service life. Service life prediction by Markov chain has the advantage over the statistical regression approach in that it can be used not only to estimate the average service life of navigation structures but also the service life of any individual structural component. Furthermore, the Markov chain prediction is based on the current condition and age of navigation structures (NS); therefore, it is simple and can be updated by new information of condition states and NS age. However, it should be noted that this study was based on synthetic data and assumed that limited amount of inspection reports with condition states are available. However, by utilizing the Latin Hypercube analytical tools to generate random numbers based on a predefined distribution, it was possible to obtain realistic values to define the transition probability, and therefore the deterioration curve.

The theory of the Markov chain is well developed and based on simple multiplications of matrices. As compared with the regression method, the Markov chain model, a probability based method, reflects better the stochastic nature of NS service life; the model provides a mathematical tool for predicting NS service life.

The procedure was shown with existing data for a combination of steel bridge-plate girders, rolled beams, weathering rolled beams and weathering plate girders, and demonstrates a model that can be implemented and used efficiently with any navigation structures. This model will be updated as more data becomes available and will also help in defining the optimum inspection time. The method is well suited for a database application.

Conclusions

In this paper, the authors have shown both analytically and by using simulations how a lock will deteriorate over time, given a known decay and repair matrix. The overall expected condition state can be misleading, and a detailed breakdown of the probability density function for the expected condition states gives a better picture of a lock's future condition state. Because the variances of the overall expected condition state is large, and it should not be assumed that the lock would follow the expected condition state curve. The cost analysis of repairs is an easy way to provide insight as to the goodness of a repair matrix.

Recommendations

Future work should strive to learn an optimal repair matrix that minimizes costs. Such a solution would add complexity to the Bayesian network. A repair cost matrix would need to be added, as well as a cost node. An analytic solution is most likely not feasible for this task due to its complexity, and simulations will be required. The added complexity would expand to a more complicated Markov chain that would require computing joint probability distributions. A special case of the Markov chain named Gibbs Sampling is used when a sample is needed from the joint probability distribution of two or more random variables. In addition, it would be interesting to increase the domain of a lock's condition state from a 1 to 5 star rating, or perhaps add the number of years that a lock has been at a particular rating.

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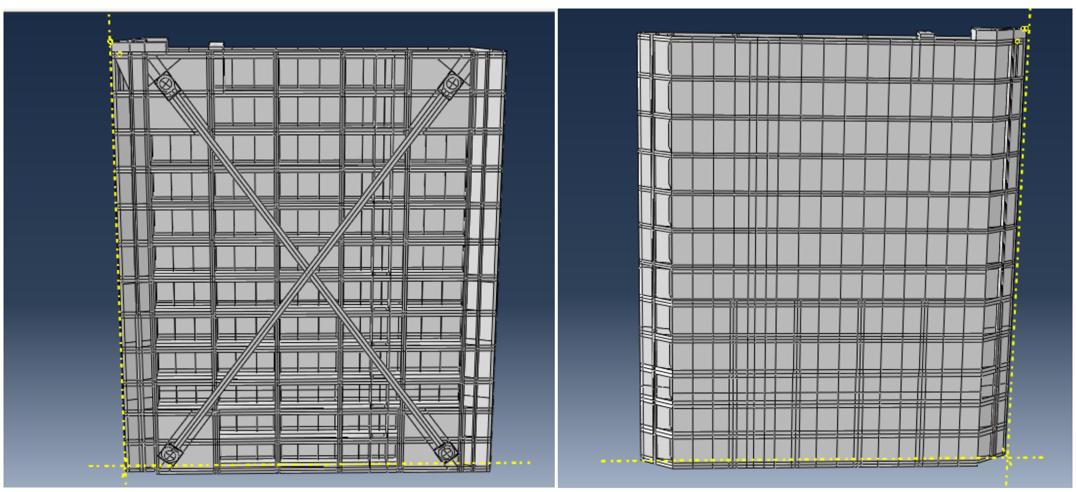
Appendix A

Lock and Dam 27 miter was used for the sample procedure of a project site using NAVSIMS. Figure A.1 shows the finite element analysis (FEA) model of Lock and Dam 27 miter gate. The gate has a horizontal configuration that consists of 13 girders and 4 intermediate diaphragms. The example will go through the procedure of an element based inspection of Girder 1, which can be done similarly with the rest of the elements on the gate.

Figure A.1. Lock and Dam 27 finite element analysis model. (Downstream view on the left and upstream view on the right.)



Getting Started

- Open Internet Explorer.
- Insert your CAC card into your CAC card reader.
- Type the following into the address bar or click the link below:
  https://navsims.usace.army.mil/

Navigator

1. In the NAVSIMS navigator, located on the left-hand side, select the **Mississippi Valley Division** (Figure A.2).
2. Select the Mississippi Valley District (Figure A.3).
3. Select the **ITL Test Lock and Dam** (Figure A.4).

Figure A.2. The Mississippi Valley Division is selected.

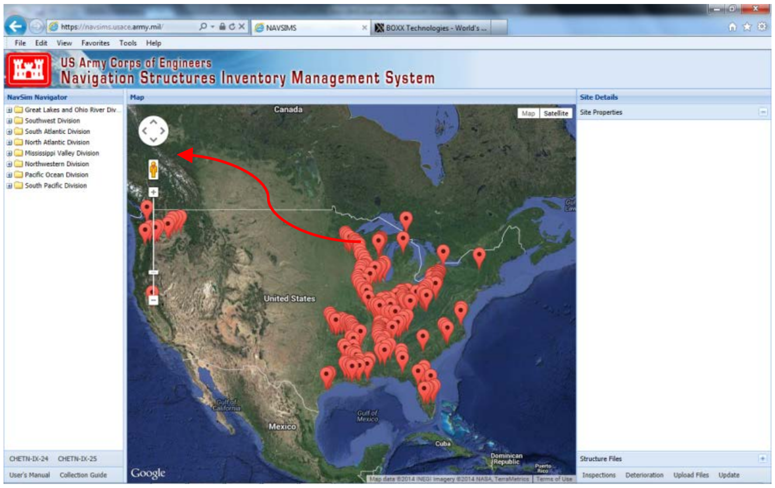
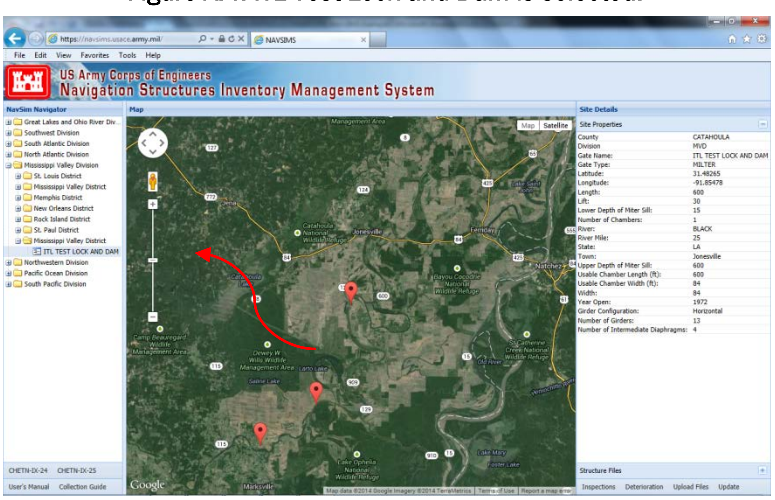


Figure A.3. The Mississippi Valley District is selected.

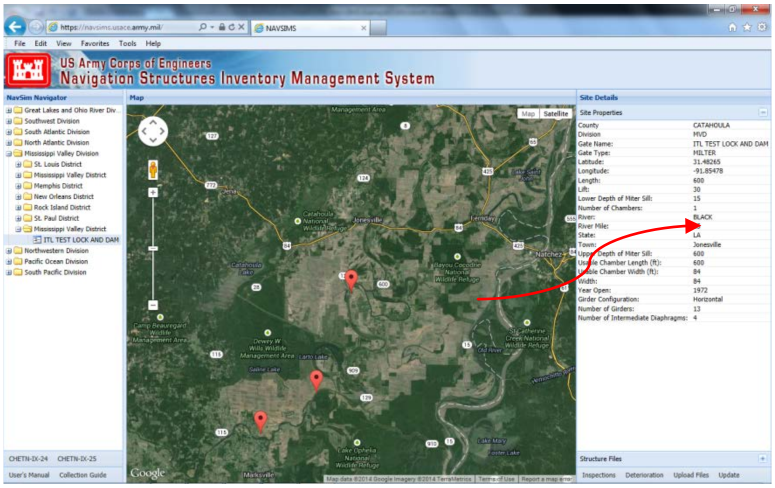
Figure A.4. ITL Test Lock and Dam is selected.



Site Details

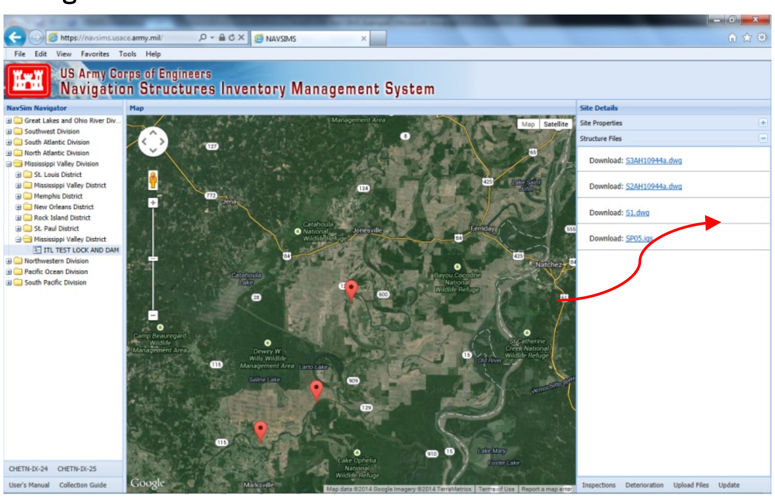
1. After selecting ITL Test Lock and Dam, the **Site Details** will appear on the right-hand side (Figure A.5).

Figure A.5. Site Details of Lock and Dam 27 appear on the right hand side.



2. Expand the structure file and a list of downloadable **Structure Files** associated with the site will appear (Figure A.6).

Figure A.6. Structure Files associated with Lock and Dam 27.

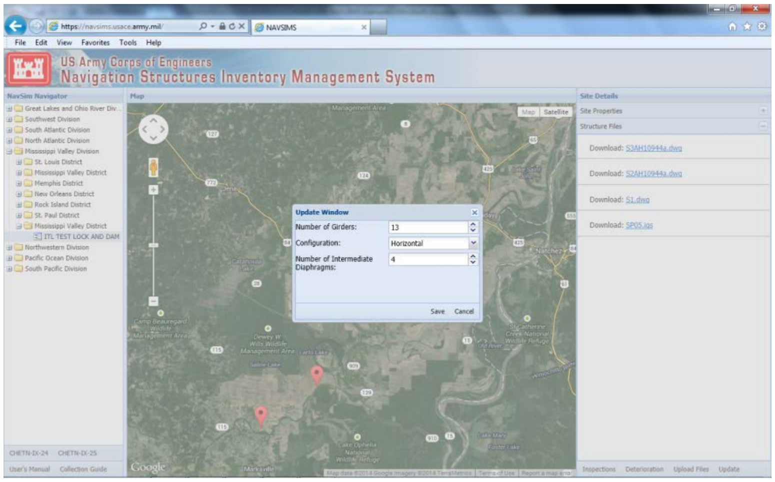


Control Panel

1. Click the **Update** (Figure A.7) button to update the girder count, intermediate diaphragm count, and site configuration (vertical or horizontal) associated with the site. When you are done entering the

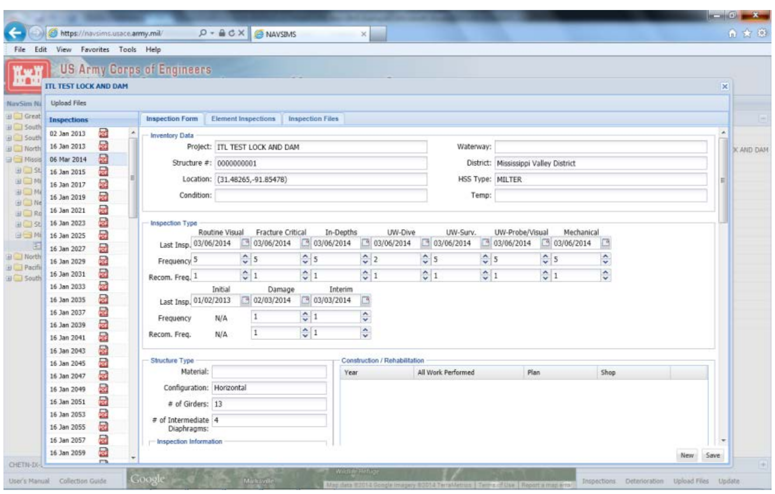
information click save to store it. For this site, the girder count is 13, the intermediate diaphragm count is 4, and the configuration is horizontal.

Figure A.7. Update Window appears to enter the girder count, intermediate diaphragm count, and site configuration of the site.



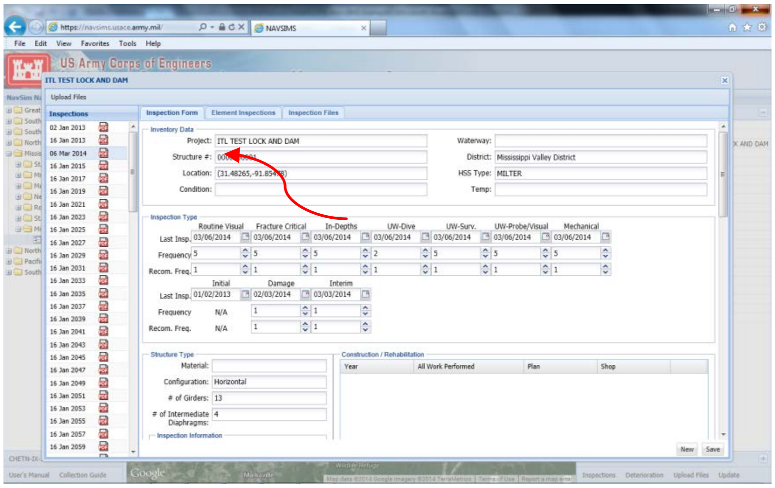
2. Press the **Inspection** button (Figure A.8) located on the bottom right panel to launch the Inspection Wizard. Under the inspection form, click **New** and enter the information associated with the site.

Figure A.8. Inspection button was selected to enter information associated with the site.



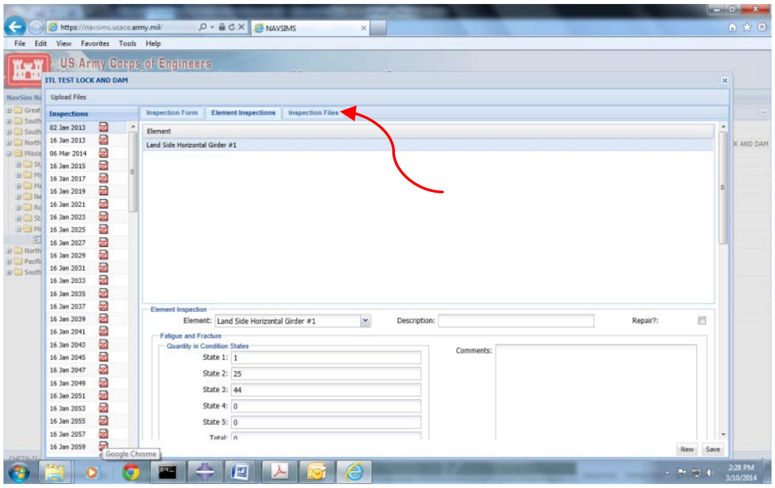
3. Click **Save** and the Inspection will be viewed in the List of Inspections (Figure A.9).

Figure 9. The saved inspection appears in the List of Inspections.



4. Under the **Element Inspection** tab click **New** (Figure A.10). For this example, the element chosen was **Land Side Horizontal Girder #1**. All information associated with this element was entered in the state fields. Note that the state fields will only accept numeric input. Click **Save** to save the element inspection. The element will appear in the element list window.

Figure A.10. The element inspection tab was selected.



Step 9 was repeated to enter element inspection information for **Land Side Horizontal Girder #2** (Figure A.11)**, and #3** (Figure A.12), respectively.

Figure A.11. Element Inspection of Land Side Horizontal Girder #2.

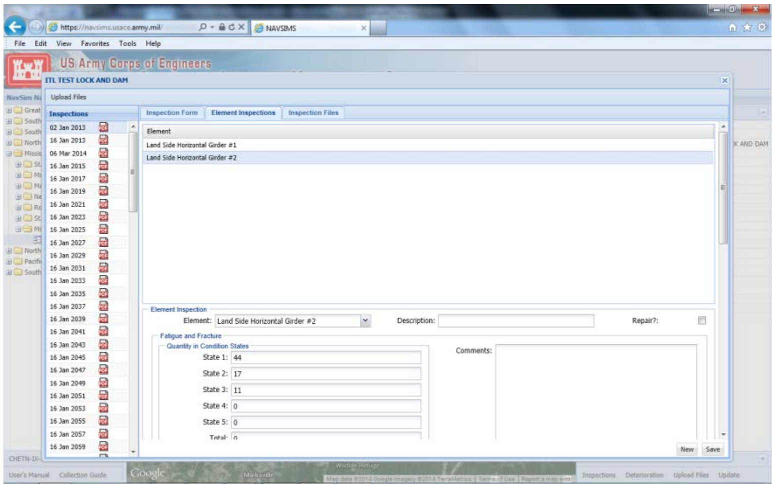
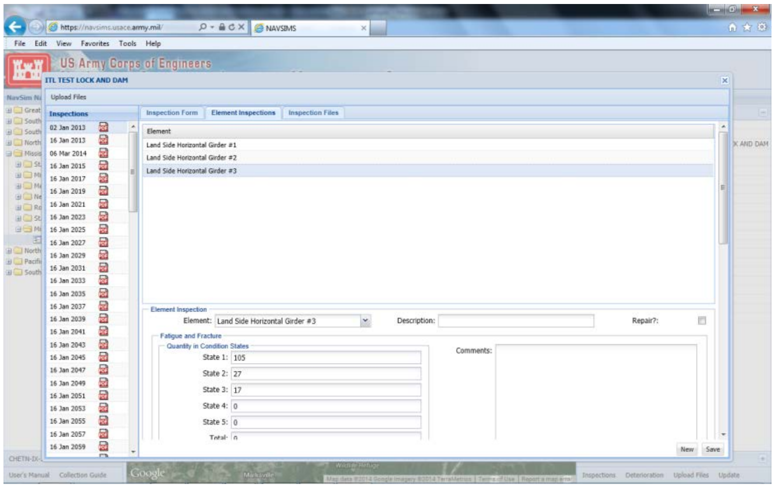


Figure A.12. Element Inspection of Land Side Horizontal Girder #3.



5. To associate a file with an inspection, click on the **Inspection Files** tab (Figure A.13).
6. Click on the **Upload Files** button in the top left hand corner to display the file wizard. A pop-up window will appear for you to select a file type. Select a file type in the drop down menu. For this example **"other files"** was selected (Figure A.14).
7. Click **Browse** to browse your desktop for the files associated with the site (Figure A.15).
8. A file selection window will appear showing the computer's structure. The file associated with this inspection was selected (Figure A.16).
9. The file is loaded and is available for review before being submitted. You have the option of clearing the file from the list or submitting the file (Figure A.17).

Figure A.13. Inspection Files was selected.

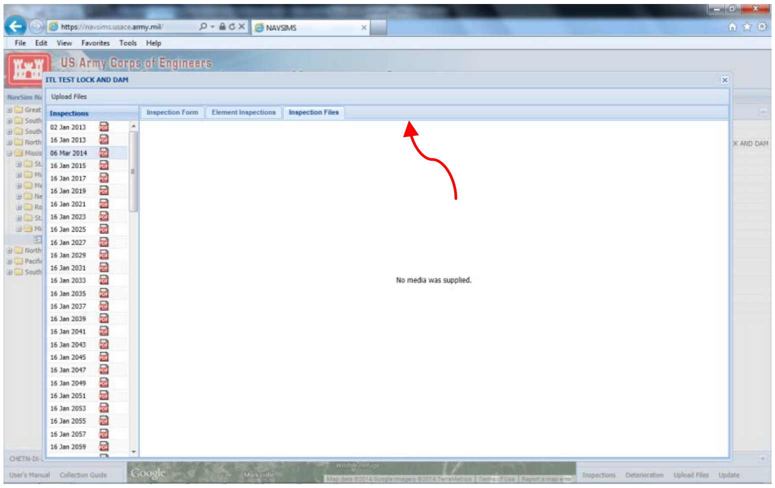


Figure A. 14. “Other Files” was selected for the file type to upload files associated with this site.

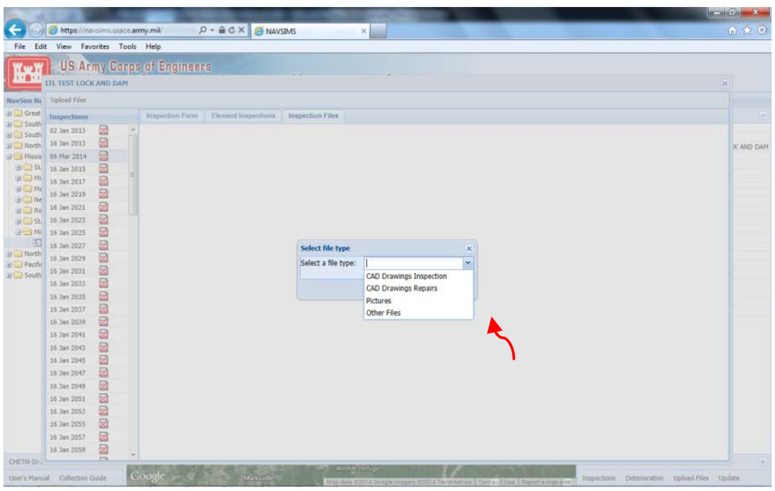


Figure A.15. Browse was selected.

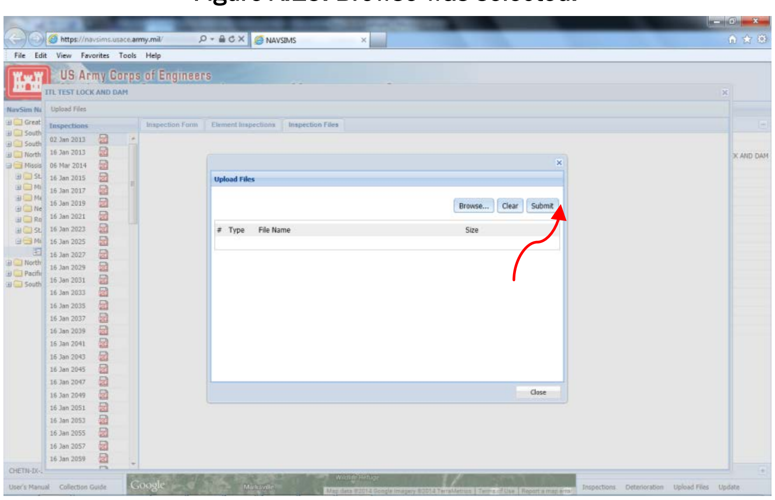


Figure A.16. The file associated with this site was selected.

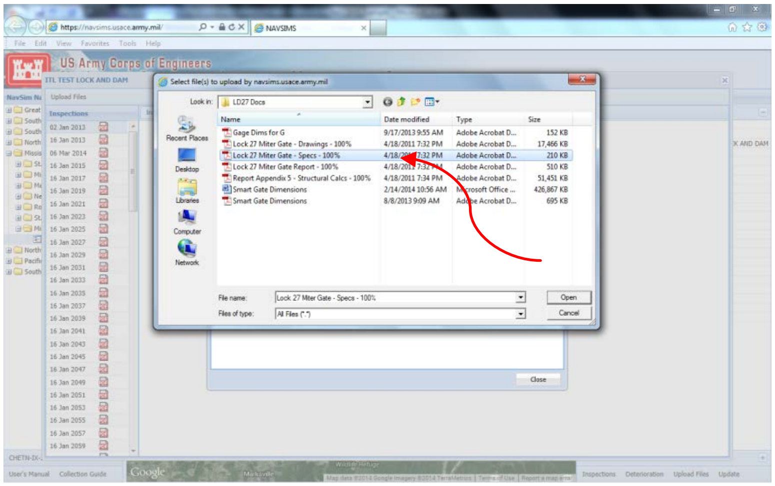
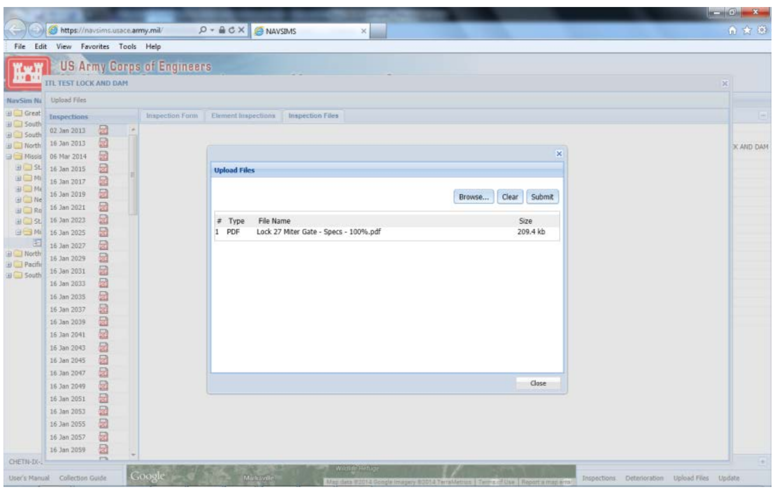


Figure A.17. The file that was selected can be reviewed before being submitted.



10. An inspection may be exported as a report in the form of a PDF file. To export an inspection report, click on the **PDF Export** to the right of the date of an inspection (Figure A.18).
11. Below is the PDF file of the inspection for this site (Figure A.19).
12. To view the deterioration graphs, click the **Deterioration** button on the control panel (Figure A.20).
13. A window will pop up with nothing in it. To view a list of matrices to graph, press the **Type** list dropdown button (Figure A.21).
14. Next select a type from the list that appears. For this example, **Land Side Horizontal Girder #1** was selected (Figure A.22).

Figure A.18. PDF export was selected to export report as a PDF file.

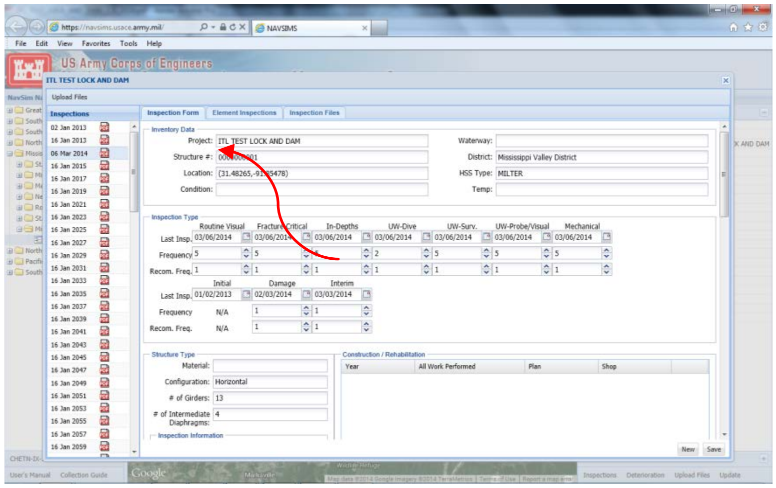


Figure A.19. PDF file on the inspection for this site.

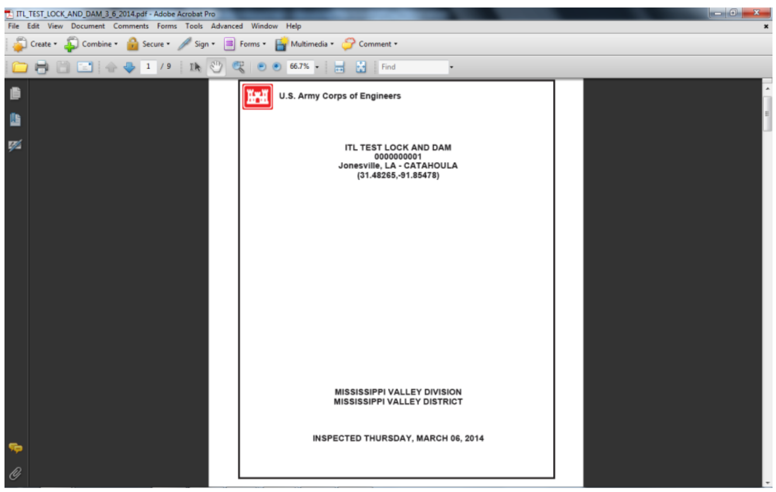


Figure A.20. Deterioration button was selection on the control panel.

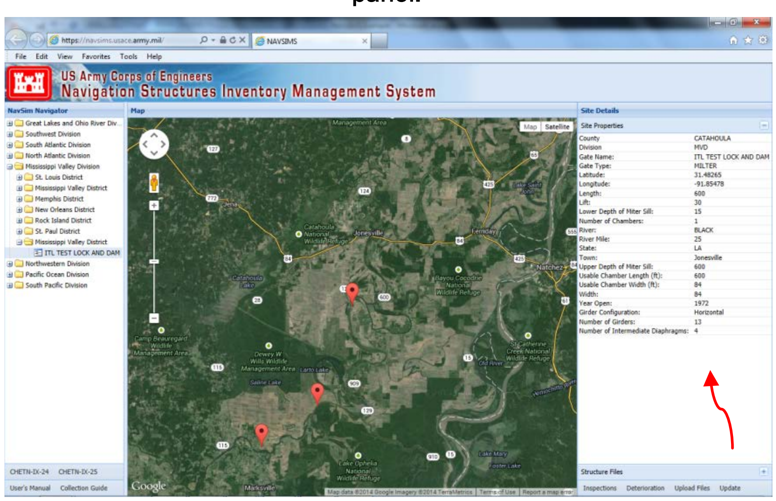


Figure A.21. Type was selected to expand the dropdown list of matrices.

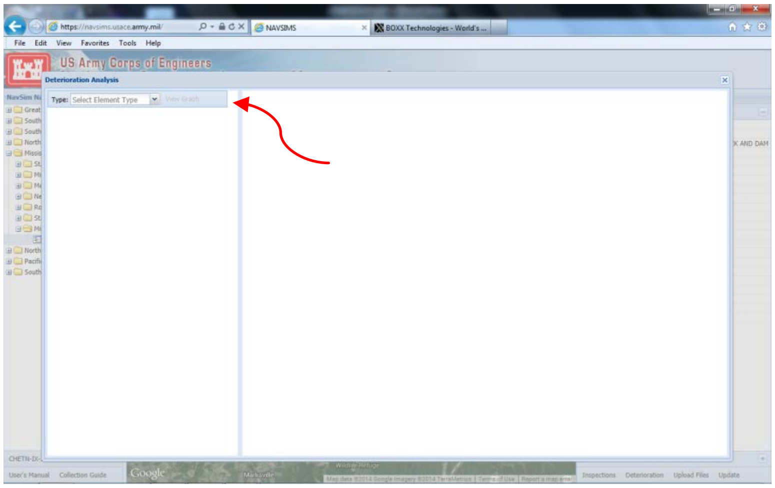
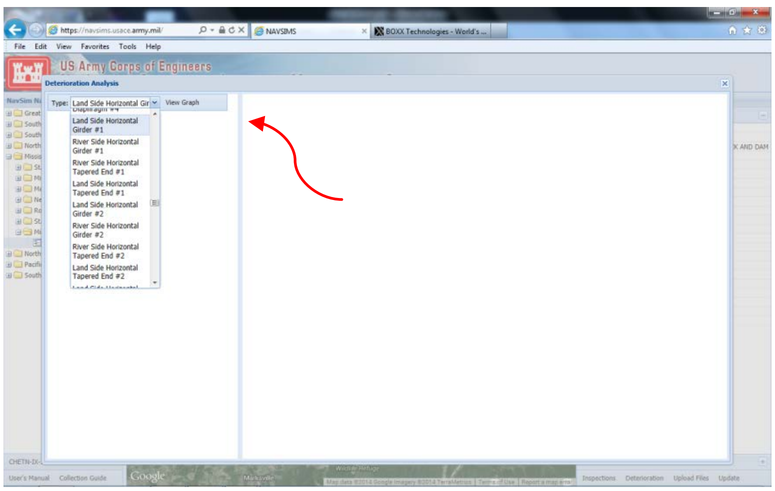


Figure A.22. Land Side Horizontal Girder #1 was selected.



15. To view the matrix for the Land Side Horizontal Girder #1, click the **View Graph** button (Figure A.23).
16. A list of matrices will appear on the left panel. Each matrix panel has two tools: **Interval Setting** tool and the **Graph** button. The Interval Setting tool is a numeric up/down tool that allows you to set the years to be displayed in the graph (Default 100). The Graph button will display the matrix as a graph on the right panel. For this example, the Interval Setting was adjusted to 50. Press Graph to graph the matrix (Figure A.24).
17. To associate a file with a site, click the **Upload Files** button on the **Control Panel** (Figure A.25).

Figure A.23. View graph was selected.

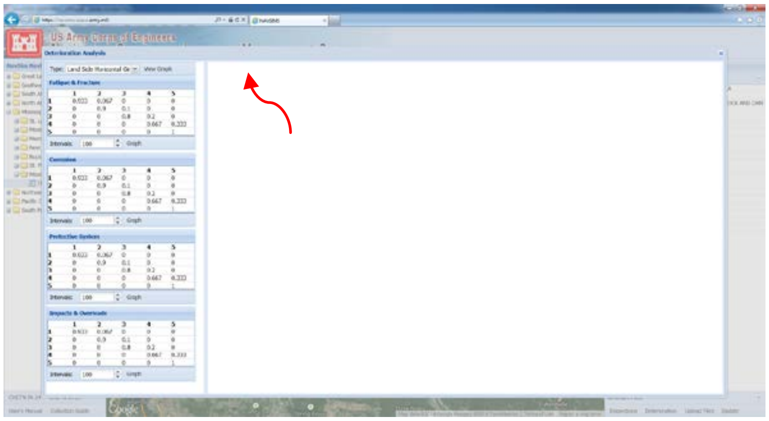


Figure A.24. Graph was selected to graph the matrix.

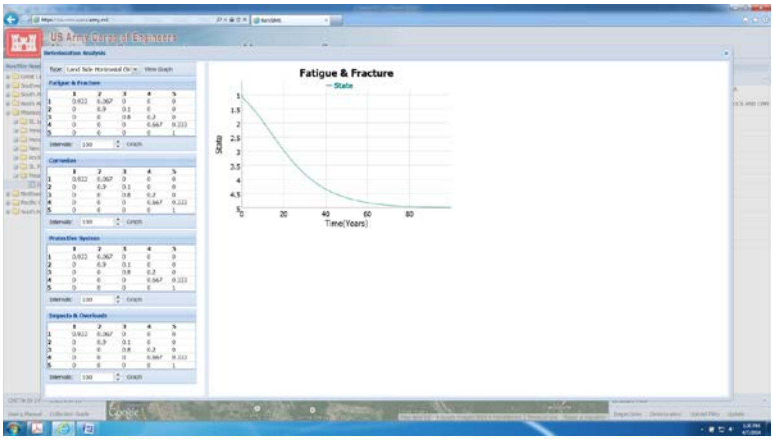
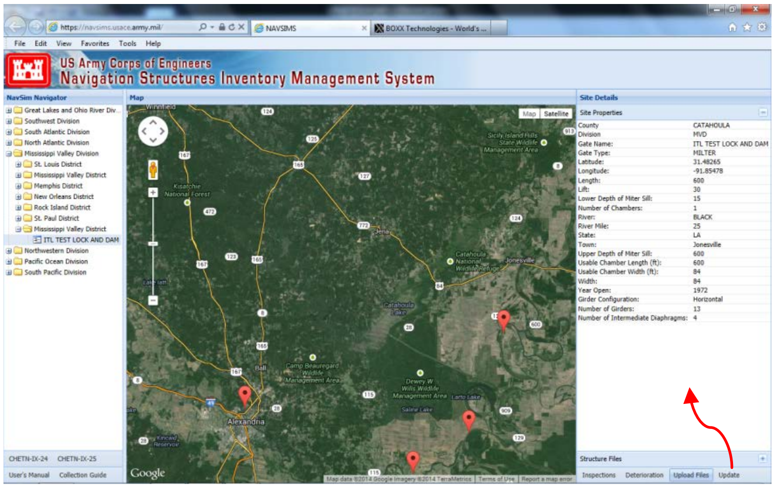
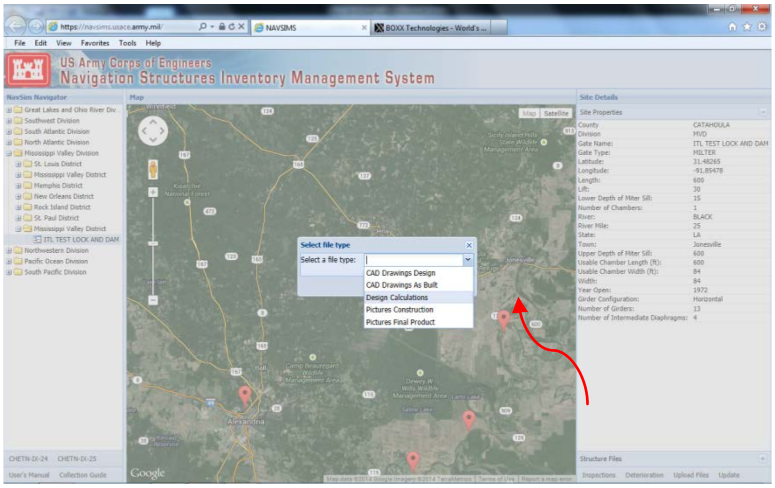


Figure A.25. Upload Files was selected on the Control Panel.



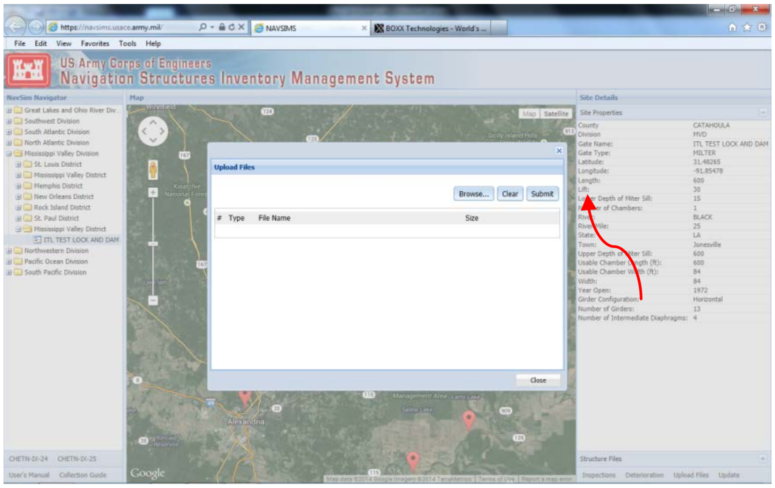
18. The **Select File type** window will pop up. For this example, **Design Calculations** was selected (Figure A.26). Click **Ok**.

Figure A.26. Design Calculations was selected as the file type for this example.



19. Click **Browse** to browse the computer's structure (Figure A.27).

Figure A.27. Browse was selected to browse the computer structure.



20. The file associated with this site was selected (Figure A.28). Click **Submit**.
21. The file will appear in the List of Downloadable Files under the Structure Files tab (Figure A.29).

Figure A.28. The file associated with this site was selected.

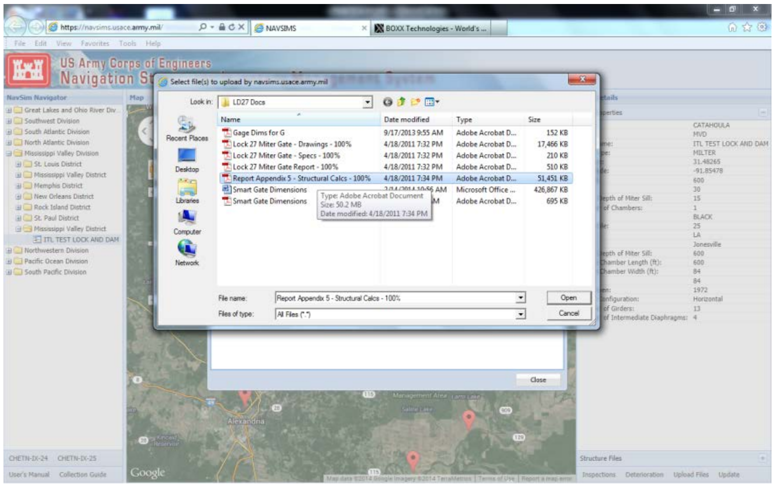
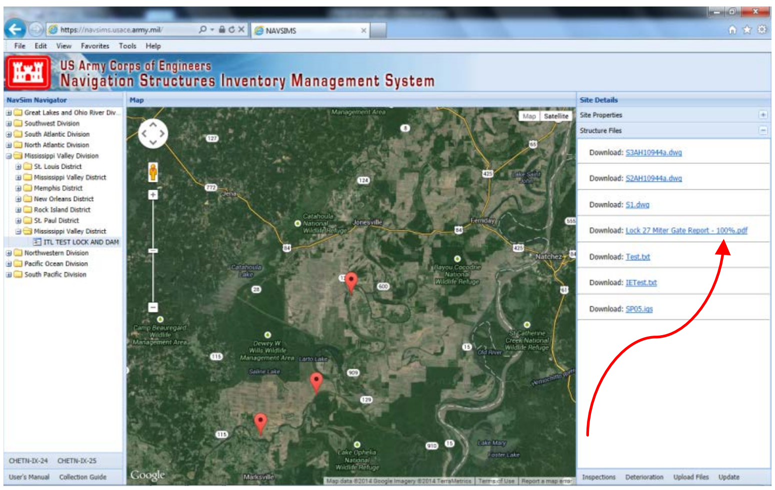


Figure A.29. The file is listed in the List of Downloadable Files.



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14. ABSTRACT

The deterioration of elements of steel hydraulic structures on the Nation's lock system is caused by combined effects of several complex phenomena: loss of protective system, corrosion, cracking and fatigue, impact, and overloads. This report presents examples of deterioration of steel hydraulic structures. A method for predicting future deterioration based on current conditions is also presented. The report includes a procedure for developing deterioration curves when condition state data is available.

15. SUBJECT TERMS

	Miter Gates	Overloads
Deterioration Modeling	Condition States	Fatigue and Fracture
Markov Chain	Corrosion	Protective System

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